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Founded by LOUIS A. BAUER
Conducted by J. A. FLEMING
With the Cooperation of Eminent Investigators

CONTENTS

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SUMMARY OF EARTH-CURRENT RECORDS FROM TUCSON, ARIZONA, FOR A COMPLETE SUNSPOT-CYCLE

BY W. J. ROONEY

Abstract—The final results of the cooperative project of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the United States Coast and Geodetic Survey, and the Bell Telephone Company, for the measurement of earth-currents at Tucson, Arizona, are summarized in eight tables. These tables give for each component yearly and monthly values of the mean diurnal variation as recorded on all days and on the ten calmest days of each month. From the yearly values the general correlation between earth-current activity and solar activity, as indicated by sunspot-numbers is apparent. The monthly values confirm in detail a number of interesting and unusual features previously reported in connection with the seasonal variation in earth-current flow at Tucson. Since the records cover a full sunspot-cycle and are quite complete and homogeneous it is believed that they afford exceptionally useful material for further study of the relationship between magnetic variations, earth-currents, and the conditions existing in the ionized layers of the upper atmosphere.

In March, 1931, the continuous registration of earth-current potentials at Tucson was undertaken as a co-operative project of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the United States Coast and Geodetic Survey, and the Bell Telephone Company. Because of the necessity for commercial use of the lines used in the measurements, the Bell Telephone Company was obliged to withdraw its support of the project early in 1943, and recording was discontinued at the end of February of that year. The period of operation—a little over eleven and one-half years—covered a full and typical sunspot-cycle, a fact that should enhance the value of the records for purposes of correlation with allied phenomena. Final reduction of the records has been completed and the data compiled in convenient form. A summary of the mean values for the eleven complete years of the system's operation are presented here to show the general variations with season and with solar activity, and to make the records available for use in other geophysical investigations.

Details of the site, lines, and instrumental equipment have been given in two previous papers [see 1, 2 of "References" at end of paper]. No

important changes in equipment or arrangement of lines were made during the entire period with the exception of a slight shift in the location of the northernmost electrode at Mammoth, Arizona, at the end of July, 1936. For this reason the data secured are remarkably homogeneous and suitable for analysis. A condensed description of the installation follows.

(1) The measuring instruments consisted of two Leeds and Northrup galvanometers with current sensitivity of about 2.5×10^{-9} ampere per millimeter scale-deflection, each used in series with a resistance of 1.5 megohms. The deflections were recorded photographically on a CIW drum-recorder.

(2) A common electrode O was located on the grounds of the Tucson Magnetic Observatory (latitude 32° 14′.8 north, longitude 110° 50′.1 west, altitude 770 meters).

(3) Using lines made available by the Bell Telephone Company, potentials were recorded continuously between electrode O and two other electrodes, namely, M, located at Mammoth (Arizona), and W, located at Wilcox (Arizona).

Prior to August, 1936, the length of line OM was 56.8 km and its direction was north 19°.5 east. After August, 1936, its length was 58.4 km and its direction was north 17°.8 east. The length of line OW was 93.9 km and its direction was east 0°.5 north for the entire period of operation.

(4) In reducing the records the eastward component is obtained directly from the records from line OW, which departs from a true west-east line by only a scant one-half degree. The true northward component is calculated from the combined records on the two lines, using the formula

$$N = N' \cos \alpha_1 - [E' \cos \alpha_2 / \sin (\alpha_2 - \alpha_1)] \qquad (1)$$

where N, is the true northward gradient; N' is the gradient recorded on the northerly line OM; E' is the gradient recorded on the easterly line OW; α_1 is the angle between OW and a true west-east line, that is, 0°.5; and α_2 is the angle between line OM and this same west-east line, namely, 70°.5 prior to August, 1936, and 72°.2 after that date. Substituting these values (1) becomes for N

For records up to August, 1936, $1.064\,OM - 0.356\,OW$ (2a)
For records after August, 1936, $1.054\,OM - 0.323\,OW$ (2b)

Since, as has been pointed out elsewhere [3], the absolute values of potential recorded on any earth-current line depend to a great extent on the electrochemical activity of the electrodes used as pick-ups, the study of earth-current flow must be largely restricted to analysis of the variations in the recorded potentials. Detailed description of the irregular fluctuations, such as those due to magnetic storms cannot readily be summarized. Hence the data presented here are those concerning the more regular, periodic variations which correspond to time of day, season of the year, or the sunspot cycle.

Tables 1 to 4 give mean diurnal-variation data by years for all days and for ten calmest days per month, while in Figure 1 will be found the

TABLE 1—*Yearly means of diurnal variation northward earth-current gradient in millivolts per kilometer, Tucson, Arizona, for all days recorded, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-hour, a positive sign indicating current flowing northward is greater than mean of day.)

105° west M. M. T. hour	Year											Mean 11 years
	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	
00–01	−0.63	−0.51	−0.39	−0.34	0.00	−0.06	−0.17	−0.15	−0.36	−0.32	−0.47	−0.31
01–02	−0.65	−0.50	−0.25	−0.21	+0.02	−0.01	−0.25	−0.34	−0.39	−0.11	−0.40	−0.28
02–03	−0.40	−0.29	−0.16	−0.02	+0.14	−0.04	+0.09	−0.02	−0.36	−0.31	−0.42	−0.16
03–04	−0.17	−0.16	+0.04	+0.01	+0.19	+0.14	−0.01	+0.05	+0.08	−0.09	−0.08	0.00
04–05	+0.09	+0.14	+0.25	+0.08	+0.28	+0.23	−0.05	+0.27	+0.03	+0.13	+0.11	+0.14
05–06	+0.44	+0.44	+0.39	+0.43	+0.72	+0.69	+0.59	+0.94	+0.56	+0.54	+0.52	+0.57
06–07	+1.09	+1.36	+1.27	+1.40	+1.88	+2.04	+2.07	+1.88	+1.40	+1.31	+1.46	+1.56
07–08	+1.98	+2.13	+1.89	+2.12	+2.83	+3.05	+3.13	+2.66	+1.99	+1.92	+1.95	+2.33
08–09	+1.36	+1.43	+1.38	+1.55	+1.83	+2.10	+2.18	+1.90	+1.46	+1.31	+1.22	+1.61
09–10	−0.21	−0.39	−0.21	−0.06	−0.46	−0.17	−0.09	−0.58	−0.45	−0.51	−0.69	−0.35
10–11	−1.65	−1.78	−1.79	−1.66	−2.46	−2.53	−2.35	−2.47	−1.93	−2.24	−1.96	−2.07
11–12	−2.23	−2.56	−2.75	−2.54	−3.50	−3.77	−3.65	−3.51	−2.70	−3.00	−2.67	−2.99
12–13	−2.08	−2.27	−2.43	−2.39	−3.09	−3.53	−3.39	−3.14	−2.54	−2.46	−2.33	−2.70
13–14	−1.30	−1.33	−1.40	−1.57	−2.10	−2.26	−2.45	−2.11	−1.64	−1.35	−1.10	−1.69
14–15	−0.25	−0.28	−0.31	−0.48	−0.74	−0.90	−0.96	−0.94	−0.51	−0.22	+0.08	−0.50
15–16	+0.68	+0.61	+0.65	+0.46	+0.24	+0.44	+0.25	+0.34	+0.46	+0.83	+0.84	+0.53
16–17	+1.10	+1.22	+1.07	+0.82	+0.96	+0.94	+1.02	+1.12	+1.12	+1.23	+1.13	+1.07
17–18	+1.41	+1.22	+1.12	+0.89	+1.07	+1.29	+1.36	+1.17	+1.30	+1.32	+1.20	+1.21
18–19	+0.97	+0.88	+0.79	+0.66	+0.94	+0.96	+0.97	+0.81	+1.00	+0.98	+0.96	+0.90
19–20	+0.51	+0.58	+0.54	+0.44	+0.56	+0.41	+0.59	+1.03	+0.75	+0.66	+0.71	+0.62
20–21	+0.38	+0.31	+0.54	+0.42	+0.47	+0.40	+0.54	+0.65	+0.64	+0.53	+0.32	+0.47
21–22	+0.10	+0.23	+0.25	+0.15	+0.26	+0.28	+0.22	+0.33	+0.30	+0.21	+0.16	+0.23
22–23	−0.19	−0.13	−0.01	−0.03	+0.06	+0.21	+0.18	+0.08	+0.09	−0.12	−0.20	−0.01
23–24	−0.36	−0.37	−0.39	−0.13	−0.12	+0.06	+0.17	−0.07	−0.28	−0.21	−0.31	−0.18
Range....	4.21	4.69	4.64	4.66	6.33	6.82	6.78	6.17	4.69	4.92	4.62	5.32
Sunspot No.	11.1	5.7	8.7	36.1	79.7	114.4	109.6	88.8	67.8	47.5	30.6	54.5

TABLE 2—*Yearly means of diurnal variation eastward earth-current gradient in millivolts per kilometer, Tucson, Arizona, for all days recorded, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-hour, a positive sign indicating current flowing eastward is greater than mean of day.)

105° west M. M. T. hour	Year											Mean 11 years
	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	
00–01	−0.46	−0.46	−0.50	−0.45	−0.54	−0.48	−0.65	−0.60	−0.69	−0.56	−0.68	−0.55
01–02	−0.54	−0.45	−0.42	−0.37	−0.45	−0.38	−0.96	−0.85	−0.69	−0.55	−0.68	−0.58
02–03	−0.56	−0.41	−0.46	−0.27	−0.47	−0.50	−0.60	−0.62	−0.66	−0.65	−0.65	−0.53
03–04	−0.47	−0.43	−0.36	−0.29	−0.24	−0.50	−0.55	−0.47	−0.28	−0.30	−0.52	−0.40
04–05	−0.34	−0.19	−0.26	−0.36	−0.33	−0.34	−0.58	−0.41	−0.36	−0.14	−0.38	−0.34
05–06	−0.10	−0.18	−0.24	−0.32	−0.09	−0.32	−0.38	−0.05	−0.09	+0.13	−0.09	−0.16
06–07	+0.10	+0.31	+0.31	+0.41	+0.35	+0.54	+0.52	+0.60	+0.55	+0.69	+0.56	+0.45
07–08	+0.91	+1.06	+1.11	+1.12	+1.52	+1.81	+1.50	+1.43	+1.43	+1.27	+1.38	+1.32
08–09	+1.05	+1.00	+1.06	+1.15	+1.37	+1.66	+1.70	+1.69	+1.49	+1.34	+1.23	+1.34
09–10	+0.45	+0.24	+0.44	+0.59	+0.66	+1.11	+0.98	+0.72	+0.61	+0.60	+0.57	+0.63
10–11	+0.03	−0.01	+0.08	+0.14	+0.06	+0.45	+0.39	+0.22	+0.02	+0.10	+0.19	+0.15
11–12	−0.15	−0.33	−0.40	−0.24	−0.38	−0.49	−0.23	−0.31	−0.38	−0.39	−0.34	−0.33
12–13	−0.38	−0.62	−0.76	−0.66	−0.66	−0.86	−0.68	−0.78	−0.61	−0.77	−0.62	−0.67
13–14	−0.39	−0.59	−0.71	−0.56	−0.59	−1.02	−0.47	−0.69	−0.61	−0.41	−0.21	−0.57
14–15	−0.07	−0.23	−0.38	−0.34	−0.35	−0.78	−0.36	−0.48	−0.34	−0.08	−0.03	−0.31
15–16	+0.22	+0.06	−0.12	+0.08	−0.13	−0.26	−0.15	−0.21	−0.08	+0.07	+0.21	−0.03
16–17	+0.36	+0.43	+0.31	+0.33	+0.15	+0.03	+0.37	+0.27	+0.21	+0.23	+0.22	+0.26
17–18	+0.60	+0.50	+0.56	+0.47	+0.48	+0.49	+0.56	+0.30	+0.46	+0.40	+0.49	+0.48
18–19	+0.26	+0.30	+0.32	+0.17	+0.27	+0.30	+0.13	+0.28	+0.37	+0.19	+0.41	+0.27
19–20	+0.07	+0.31	+0.28	+0.04	+0.15	−0.02	+0.08	+0.39	+0.06	+0.05	+0.19	+0.15
20–21	+0.09	+0.06	+0.26	+0.02	−0.03	−0.04	−0.17	0.00	+0.06	−0.22	−0.03	0.00
21–22	−0.15	+0.07	+0.10	−0.15	−0.10	−0.07	−0.10	+0.12	−0.01	−0.22	−0.20	−0.06
22–23	−0.31	−0.14	+0.04	−0.10	−0.33	−0.12	−0.10	−0.35	−0.05	−0.28	−0.42	−0.20
23–24	−0.29	−0.32	−0.33	−0.30	−0.35	−0.20	−0.27	−0.18	−0.46	−0.53	−0.56	−0.34
Range....	1.61	1.68	1.87	1.81	2.18	2.84	2.66	2.54	2.38	2.11	2.06	2.01
Sunspot No.	11.1	5.7	8.7	36.1	79.7	114.4	109.6	88.8	67.8	47.5	30.6	54.5

TABLE 3—*Yearly means of diurnal variation northward earth-current gradient in millivolts per ki[lo]meter, Tucson, Arizona, for ten calmest days in each month, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on t[he] half-hour, a positive sign indicating current flowing northward is greater than mean of day.)

105° west M. M. T. hour	Year											Mea[n] 11 year[s]
	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	
00–01	−0.24	−0.29	−0.22	−0.24	+0.02	+0.04	−0.02	−0.21	−0.18	−0.31	−0.29	−0.
01–02	−0.17	−0.12	−0.14	−0.11	−0.06	−0.08	−0.08	−0.28	−0.16	−0.02	−0.26	−0.
02–03	−0.01	+0.04	−0.02	+0.05	+0.09	+0.05	0.00	−0.03	+0.10	−0.04	−0.14	+0.0
03–04	+0.06	+0.11	+0.15	+0.23	+0.24	+0.27	+0.23	+0.26	+0.15	+0.04	+0.12	+0.1
04–05	+0.22	+0.27	+0.31	+0.25	+0.43	+0.29	+0.26	+0.34	+0.20	+0.34	+0.20	+0.2
05–06	+0.52	+0.60	+0.61	+0.59	+0.77	+0.96	+0.86	+1.03	+0.66	+0.74	+0.64	+0.7
06–07	+1.20	+1.40	+1.44	+1.46	+1.96	+2.22	+2.20	+2.06	+1.54	+1.66	+1.61	+1.7
07–08	+1.74	+2.15	+2.17	+2.29	+2.96	+3.46	+3.16	+2.93	+2.41	+2.38	+1.98	+2.5
08–09	+1.26	+1.44	+1.62	+1.67	+2.06	+2.34	+2.32	+2.24	+1.44	+1.34	+1.32	+1.7
09–10	−0.38	0.00	−0.18	−0.02	−0.42	−0.10	−0.23	−0.29	−0.47	−0.56	−0.48	−0.2
10–11	−1.89	−1.88	−1.89	−1.90	−2.57	−2.50	−2.55	−2.30	−2.22	−2.43	−2.13	−2.2
11–12	−2.45	−2.77	−2.98	−2.79	−3.49	−3.87	−3.81	−3.45	−3.06	−3.12	−2.89	−3.1
12–13	−2.16	−2.51	−2.60	−2.61	−3.10	−3.68	−3.49	−3.23	−2.70	−2.53	−2.47	−2.8
13–14	−1.30	−1.57	−1.56	−1.60	−2.08	−2.38	−2.46	−2.30	−1.82	−1.55	−1.35	−1.8
14–15	−0.26	−0.46	−0.43	−0.49	−0.90	−0.86	−1.01	−1.09	−0.65	−0.48	−0.19	−0.6
15–16	+0.51	+0.38	+0.52	+0.38	+0.22	+0.39	+0.28	+0.15	+0.50	+0.61	+0.54	+0.4
16–17	+0.87	+0.95	+0.92	+0.82	+0.76	+1.05	+0.94	+0.92	+1.04	+1.12	+1.04	+0.9
17–18	+0.94	+0.98	+0.91	+1.00	+1.03	+1.08	+1.13	+1.04	+1.10	+1.14	+0.99	+1.0
18–19	+0.70	+0.62	+0.61	+0.55	+0.84	+0.66	+0.92	+0.89	+0.65	+0.79	+0.85	+0.7
19–20	+0.39	+0.43	+0.39	+0.24	+0.54	+0.32	+0.54	+0.68	+0.40	+0.50	+0.55	+0.4
20–21	+0.39	+0.27	+0.29	+0.23	+0.35	+0.17	+0.41	+0.32	+0.40	+0.37	+0.24	+0.3
21–22	+0.10	+0.22	+0.24	+0.11	+0.15	+0.14	+0.19	+0.26	+0.24	+0.20	+0.27	+0.1
22–23	+0.10	0.00	−0.02	+0.09	+0.14	+0.04	+0.20	+0.13	+0.15	+0.09	−0.02	+0.0
23–24	−0.11	−0.07	−0.24	−0.08	+0.09	+0.07	+0.02	+0.03	+0.16	−0.18	−0.18	−0.0
Range. . . .	4.19	4.92	5.15	5.08	6.45	7.33	6.97	6.38	5.47	5.50	4.87	5.6
Sunspot No.	11.1	5.7	8.7	36.1	79.7	114.4	109.6	88.8	67.8	47.5	30.6	54.5

TABLE 4—*Yearly means of diurnal variation eastward earth-current gradient in millivolts per kilometer, Tucson, Arizona, for ten calmest days in each month, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-hour, a positive sign indicating current flowing eastward is greater than mean of day.)

105° west M. M. T. hour	Year											Mean 11 years
	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	
00–01	−0.32	−0.39	−0.23	−0.34	−0.43	−0.23	−0.49	−0.46	−0.40	−0.53	−0.67	−0.41
01–02	−0.32	−0.26	−0.31	−0.32	−0.39	−0.35	−0.42	−0.57	−0.34	−0.29	−0.48	−0.37
02–03	−0.48	−0.22	−0.32	−0.28	−0.36	−0.28	−0.47	−0.28	−0.19	−0.26	−0.54	−0.33
03–04	−0.30	−0.25	−0.19	−0.17	−0.21	−0.22	−0.19	−0.16	−0.04	−0.22	−0.26	−0.20
04–05	−0.27	−0.16	−0.17	−0.17	−0.17	−0.24	−0.14	−0.26	−0.13	−0.01	−0.34	−0.19
05–06	−0.14	−0.15	−0.12	−0.17	−0.04	−0.05	−0.03	+0.05	+0.10	+0.24	−0.09	−0.04
06–07	+0.21	+0.31	+0.46	+0.40	+0.45	+0.75	+0.62	+0.72	+0.63	+0.88	+0.52	+0.54
07–08	+0.79	+1.22	+1.38	+1.28	+1.50	+2.19	+1.81	+1.53	+1.43	+1.55	+1.29	+1.45
08–09	+0.88	+1.17	+1.34	+1.19	+1.50	+2.11	+1.79	+1.71	+1.52	+1.31	+1.16	+1.43
09–10	+0.32	+0.39	+0.43	+0.49	+0.53	+1.07	+0.74	+0.84	+0.58	+0.43	+0.48	+0.57
10–11	−0.26	+0.02	−0.10	−0.15	−0.16	+0.24	−0.04	+0.34	−0.38	−0.38	−0.09	−0.09
11–12	−0.40	−0.43	−0.64	−0.47	−0.64	−0.92	−0.44	−0.25	−0.82	−0.75	−0.53	−0.57
12–13	−0.46	−0.85	−0.89	−0.83	−0.66	−1.34	−1.00	−0.95	−0.93	−0.86	−0.68	−0.86
13–14	−0.34	−0.87	−0.87	−0.64	−0.64	−1.36	−0.90	−0.97	−0.88	−0.74	−0.51	−0.79
14–15	−0.12	−0.50	−0.67	−0.40	−0.46	−1.05	−0.54	−0.86	−0.63	−0.53	−0.23	−0.54
15–16	+0.11	−0.28	−0.25	−0.10	−0.24	−0.47	−0.20	−0.60	−0.20	−0.14	−0.09	−0.22
16–17	+0.19	+0.26	+0.12	+0.10	+0.10	+0.07	+0.19	+0.10	+0.03	+0.14	+0.41	+0.16
17–18	+0.40	+0.40	+0.43	+0.31	+0.34	+0.26	+0.26	+0.11	+0.36	+0.36	+0.36	+0.33
18–19	+0.33	+0.22	+0.30	+0.06	+0.11	+0.05	+0.03	+0.08	+0.12	+0.08	+0.26	+0.15
19–20	+0.19	+0.16	+0.23	−0.05	+0.09	+0.02	0.00	+0.11	+0.06	0.00	+0.23	+0.09
20–21	+0.19	+0.19	+0.30	+0.02	+0.04	−0.03	−0.11	+0.02	−0.02	+0.02	+0.17	+0.07
21–22	+0.08	+0.14	+0.22	+0.06	−0.03	+0.06	−0.20	−0.11	+0.03	+0.05	+0.17	+0.04
22–23	−0.19	+0.11	+0.08	−0.01	−0.14	−0.06	−0.12	−0.01	+0.12	−0.14	−0.13	−0.04
23–24	−0.16	−0.19	−0.32	−0.02	−0.15	−0.15	−0.18	−0.17	+0.01	−0.40	−0.37	−0.19
Range. . . .	1.34	2.09	2.27	2.11	2.16	3.55	2.81	2.68	2.45	2.41	1.97	2.31
Sunspot No.	11.1	5.7	8.7	36.1	79.7	114.4	109.6	88.8	67.8	47.5	30.6	54.5

mean curves of this variation for the entire eleven-year period. These curves are very like those already published for this station [2], which showed the variation for the years 1932-34, but their amplitudes are approximately 20 per cent greater. This difference in amplitude exists because the earlier curves were representative of conditions near the sunspot-minimum, while the data presented in Figure 1 are average values over the complete sunspot-cycle. The last two lines in each of

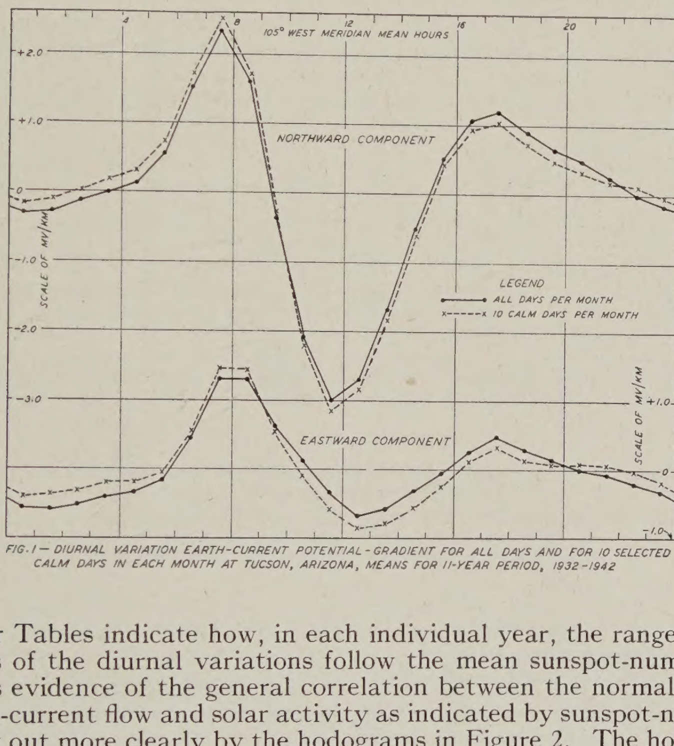

FIG. 1 — DIURNAL VARIATION EARTH-CURRENT POTENTIAL-GRADIENT FOR ALL DAYS AND FOR 10 SELECTED CALM DAYS IN EACH MONTH AT TUCSON, ARIZONA, MEANS FOR 11-YEAR PERIOD, 1932-1942

the four Tables indicate how, in each individual year, the ranges or amplitudes of the diurnal variations follow the mean sunspot-numbers.

This evidence of the general correlation between the normal activity in earth-current flow and solar activity as indicated by sunspot-number is brought out more clearly by the hodograms in Figure 2. The hodograms are formed by joining points which mark the successive positions of vectors defining the magnitude and direction of the potential-gradient, and hence of current-flow, for each hour of the day. The central pair of hodograms are constructed from the same data as the curves in Figure 1 and represent average conditions over the entire sunspot-cycle. The hodograms on either side are those for the year 1932, near the sunspot-minimum, and the year 1937, at about the time of the sunspot-maximum. It will be noted that the hodograms constructed from the data recorded on the ten calmest days of each month do not differ greatly from the data for all days. At Tucson, as elsewhere, an increase in the frequency and strength of disturbances accompanies high sunspot-numbers, but the similarity of the two grams of each pair shows that disturbance-effects have been effectively averaged out, so that the differences in the three

cases represent real changes in the normal activity as evidenced by the diurnal variation.

Considerable particular as well as general correlation between sun-spot-numbers and the range of the diurnal variation in earth-currents has been shown in the data secured at a number of other stations [4]. In the case of Tucson a much closer correlation than that given by comparison of yearly means is also indicated but the unusual and rather complicated seasonal variation which occurs at this station [2] makes it somewhat difficult to evaluate.

The Tucson records are summarized in a different grouping in Tables 5 to 8 which give mean diurnal-variation data by months instead of

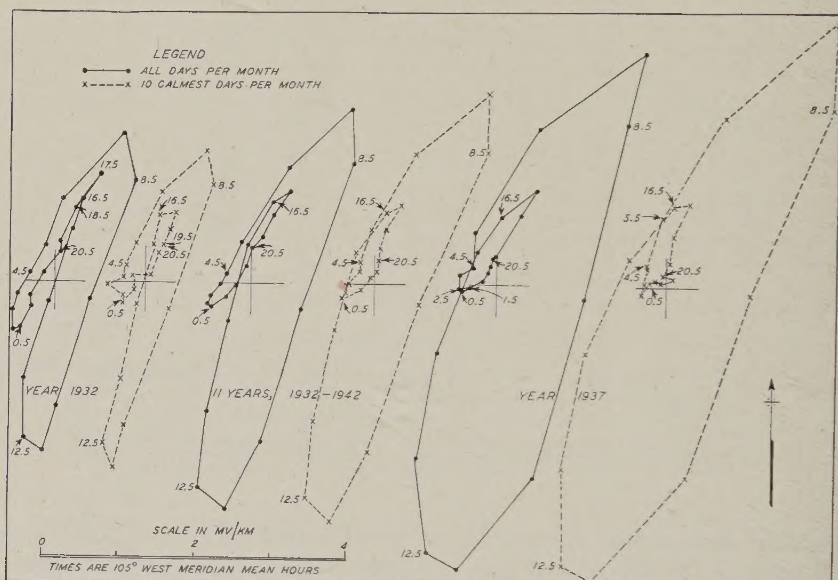

FIG. 2—MEAN HODOGRAPHS OF DIURNAL VARIATION IN EARTH-CURRENT POTENTIAL-GRADIENT FOR ALL DAYS AND FOR 10 CALMEST DAYS IN EACH MONTH AT TUCSON, ARIZONA, FOR YEARS 1932 AND 1937 AND FOR 11-YEARS 1932–42

by years. Here again values are given for all days and for the ten calmest days in each month. These Tables are of chief interest with reference to the seasonal variation in earth-current activity. Attention has already been called to this feature of the records at Tucson and to the fact that the seasonal changes there are markedly different from those usually noted in earth-current records at other widely distributed stations [2, 3]. These differences and their significance are discussed briefly in the following paragraphs.

At most stations where earth-currents have been investigated the seasonal changes are chiefly changes in intensity, accompanied by only minor shifts in phase or in the phase-relationship between the two components. Such changes are readily described quantitatively. Tucson, however, is located in the so-called transition-belt where the diurnal

ABLE 5—*Eleven-year monthly means of diurnal variation northward earth-current gradient in millivolts per kilometer, Tucson, Arizona, for all days recorded, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-hour positive sign indicating current flowing northward is greater than mean of day.)

105° west M. M. T. hour	Month												Mean 11 years
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
00-01	−0.57	−0.38	−0.25	−0.20	+0.03	−0.18	−0.24	−0.17	−0.11	−0.14	−0.48	−0.80	−0.31
01-02	−0.52	−0.46	−0.22	+0.02	−0.10	−0.14	−0.05	−0.08	+0.03	−0.41	−0.54	−0.64	−0.28
02-03	−0.41	−0.38	−0.24	+0.13	−0.06	+0.21	−0.11	+0.13	+0.21	−0.34	−0.41	−0.56	−0.16
03-04	−0.51	−0.42	+0.10	+0.21	+0.40	+0.59	+0.57	+0.42	−0.01	−0.34	−0.35	−0.39	0.00
04-05	−0.34	−0.20	−0.14	+0.42	+0.76	+0.85	+0.70	+0.66	+0.21	−0.48	−0.23	−0.46	+0.14
05-06	−0.44	−0.07	+0.18	+0.83	+1.50	+1.59	+1.45	+1.42	+0.78	+0.17	−0.03	−0.44	+0.57
06-07	−0.12	+0.12	+1.20	+2.17	+2.43	+2.69	+2.66	+3.22	+2.50	+1.61	+0.47	−0.20	+1.56
07-08	+0.93	+0.96	+2.46	+3.17	+2.61	+2.72	+2.97	+3.87	+3.32	+2.49	+1.58	+0.73	+2.33
08-09	+2.28	+1.17	+1.96	+1.64	+1.21	+1.14	+1.89	+1.67	+1.35	+1.71	+1.48	+1.50	+1.61
09-10	+2.36	+0.64	−0.06	−1.03	−1.55	−1.34	−1.20	−2.31	−1.54	−0.50	+0.38	+1.60	−0.35
10-11	+1.05	−0.34	−2.00	−3.11	−3.46	−3.77	−3.84	−4.49	−3.01	−1.95	−0.78	+0.60	−2.07
11-12	−1.78	−1.41	−2.79	−3.31	−3.73	−4.33	−4.46	−4.56	−3.40	−2.78	−2.06	−1.21	−2.99
12-13	−2.72	−2.15	−2.76	−2.57	−2.65	−3.27	−3.74	−3.54	−2.82	−2.09	−2.06	−1.78	−2.70
13-14	−2.31	−1.38	−1.91	−2.08	−1.62	−1.97	−2.35	−2.02	−1.20	−0.76	−0.97	−1.42	−1.69
14-15	−1.32	−0.46	−0.76	−1.06	−0.56	−0.60	−0.58	−0.06	+0.16	+0.29	−0.19	−0.70	−0.50
15-16	+0.04	+0.40	+0.37	+0.02	+0.41	+0.86	+0.83	+1.13	+1.23	+0.70	+0.36	+0.05	+0.53
16-17	+1.01	+0.82	+0.98	+0.98	+1.20	+1.56	+1.68	+1.61	+1.03	+0.48	+0.68	+0.75	+1.07
17-18	+1.03	+0.82	+1.25	+1.64	+1.34	+1.63	+1.93	+1.42	+0.54	+0.49	+1.03	+1.18	+1.21
18-19	+0.92	+0.96	+1.07	+1.12	+0.91	+0.94	+1.01	+0.57	+0.23	+0.91	+0.98	+1.02	+0.90
19-20	+0.83	+0.84	+0.90	+0.61	+0.40	+0.25	+0.10	+0.34	+0.43	+0.74	+0.84	+0.89	+0.62
20-21	+0.63	+0.74	+0.50	+0.30	+0.31	+0.26	+0.19	+0.42	+0.47	+0.47	+0.62	+0.64	+0.47
21-22	+0.26	+0.29	+0.31	+0.14	+0.32	+0.24	+0.35	+0.19	−0.12	+0.21	+0.28	+0.23	+0.23
22-23	−0.14	+0.24	−0.05	−0.24	+0.26	+0.01	+0.30	+0.23	−0.06	+0.17	−0.06	−0.16	−0.01
23-24	−0.33	−0.30	−0.21	+0.19	−0.17	+0.04	+0.03	+0.02	−0.10	−0.41	−0.41	−0.51	−0.18
Range	5.08	3.32	5.25	6.48	6.34	7.05	7.43	8.36	6.72	5.27	3.64	3.38	5.32
Sunspot No.	50.2	56.1	49.5	53.3	54.9	57.6	60.7	61.6	53.1	53.9	53.5	50.9	54.5

ABLE 6—*Eleven-year monthly means of diurnal variation eastward earth-current gradient in millivolts per kilometer, Tucson, Arizona, for all days recorded, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-hour, positive sign indicating current flowing eastward is greater than mean of day.)

105° west M. M. T. hour	Month												Mean 11 years
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
00-01	−0.42	−0.56	−0.73	−0.71	−0.38	−0.71	−0.48	−0.51	−0.56	−0.47	−0.42	−0.69	−0.55
01-02	−0.58	−0.69	−0.67	−0.52	−0.60	−0.31	−0.38	−0.36	−0.61	−0.81	−0.67	−0.60	−0.58
02-03	−0.56	−0.57	−0.74	−0.56	−0.41	−0.26	−0.43	−0.27	−0.39	−0.89	−0.76	−0.57	−0.53
03-04	−0.73	−0.72	−0.46	−0.32	−0.13	+0.02	+0.15	−0.13	−0.46	−0.84	−0.59	−0.66	−0.40
04-05	−0.64	−0.71	−0.24	−0.24	+0.06	−0.02	+0.08	+0.03	−0.29	−0.70	−0.72	−0.59	−0.34
05-06	−0.57	−0.30	−0.03	+0.14	−0.03	−0.19	−0.08	+0.11	+0.17	−0.01	−0.32	−0.62	−0.16
06-07	−0.37	−0.07	+0.42	+0.68	+0.76	+0.64	+0.49	+1.19	+1.25	+0.82	0.00	−0.36	+0.45
07-08	+0.04	+0.08	+1.28	+2.06	+1.62	+1.47	+1.71	+2.58	+2.83	+1.67	+0.80	−0.01	+1.32
08-09	+1.08	+0.42	+1.34	+1.77	+1.18	+1.12	+1.37	+1.99	+2.06	+1.79	+1.26	+0.55	+1.34
09-10	+2.22	+0.80	+0.53	+0.46	−0.19	−0.63	−0.21	−0.16	+0.86	+0.99	+1.26	+1.56	+0.63
10-11	+3.08	+1.04	−0.34	−0.19	−1.02	−1.58	−1.26	−1.39	−0.42	+0.10	+1.26	+2.23	+0.15
11-12	+1.70	+0.87	−0.11	−0.40	−1.19	−1.70	−1.64	−1.89	−1.27	−0.51	+0.24	+1.55	−0.33
12-13	−0.39	+0.02	−0.08	−0.72	−1.14	−1.12	−1.34	−1.52	−1.38	−0.51	−0.46	+0.41	−0.67
13-14	−1.47	−0.18	−0.37	−0.87	−0.41	−0.32	−0.57	−0.60	−0.80	−0.29	−0.38	−0.58	−0.57
14-15	−1.90	−0.29	−0.27	−0.53	+0.23	+0.56	+0.34	+0.27	−0.47	−0.12	−0.48	−1.05	−0.31
15-16	−1.43	−0.27	−0.07	−0.51	+0.68	+1.36	+0.98	+0.62	+0.01	+0.07	−0.58	−1.03	−0.03
16-17	−0.28	−0.04	+0.21	+0.12	+0.90	+1.39	+1.27	+0.80	−0.12	−0.03	−0.39	−0.57	+0.26
17-18	+0.30	+0.29	+0.67	+0.69	+0.86	+1.02	+1.26	+0.69	+0.04	−0.02	+0.05	−0.05	+0.48
18-19	+0.19	+0.43	+0.53	+0.54	+0.29	+0.44	+0.29	+0.23	−0.10	+0.08	+0.30	+0.14	+0.27
19-20	+0.37	+0.48	+0.21	+0.05	+0.09	−0.11	−0.24	−0.27	+0.02	+0.29	+0.41	+0.44	+0.15
20-21	+0.24	+0.23	−0.12	−0.05	−0.20	−0.14	−0.35	−0.35	−0.02	+0.18	+0.23	+0.44	0.00
21-22	+0.24	+0.12	−0.22	−0.19	−0.20	−0.20	−0.42	−0.36	−0.22	+0.09	+0.30	+0.27	−0.06
22-23	+0.10	−0.08	−0.39	−0.38	−0.24	−0.28	−0.12	−0.33	−0.18	−0.49	−0.07	+0.09	−0.20
23-24	−0.14	−0.32	−0.42	−0.26	−0.55	−0.36	−0.40	−0.50	−0.21	−0.46	−0.18	−0.30	−0.34
Range	4.98	1.76	2.08	2.93	2.81	3.17	3.35	4.47	4.21	2.68	2.02	3.28	2.01
Sunspot No.	50.2	56.1	49.5	53.3	54.9	57.6	60.7	61.6	53.1	53.9	53.5	50.9	54.5

TABLE 7—*Eleven-year monthly means of diurnal variation northward earth-current gradient in millivol[ts per] kilometer, Tucson, Arizona, for ten calmest days in each month, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half[-hour,] a positive sign indicating current flowing northward is greater than the means of day.)

105° west M. M. T. hour	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
00–01	−0.48	−0.31	−0.20	0.00	−0.04	+0.02	−0.12	+0.08	+0.03	−0.08	−0.58	−0.48
01–02	−0.42	−0.41	−0.20	+0.07	+0.04	+0.08	−0.03	+0.07	+0.15	−0.21	−0.35	−0.47
02–03	−0.35	−0.35	−0.02	+0.10	+0.18	+0.28	+0.03	+0.20	+0.37	+0.03	−0.15	−0.31
03–04	−0.34	−0.15	0.00	+0.25	+0.50	+0.54	+0.50	+0.57	+0.42	+0.08	−0.12	−0.27
04–05	−0.28	−0.15	+0.20	+0.41	+0.79	+0.84	+0.70	+0.85	+0.30	+0.01	−0.08	−0.26
05–06	−0.20	+0.08	+0.45	+0.93	+1.36	+1.58	+1.44	+1.43	+1.26	+0.48	+0.22	−0.16
06–07	−0.01	+0.34	+1.23	+2.19	+2.47	+2.63	+2.78	+3.27	+2.87	+1.84	+0.83	+0.03
07–08	+1.11	+1.15	+2.55	+3.44	+2.90	+2.80	+3.06	+4.25	+3.57	+2.81	+1.87	+0.79
08–09	+2.44	+1.51	+1.92	+1.99	+1.18	+0.81	+1.94	+1.98	+1.55	+1.88	+1.53	+1.71
09–10	+2.74	+0.92	−0.03	−0.86	−1.66	−1.40	−1.16	−2.33	−1.28	−0.66	+0.48	+1.85
10–11	+1.06	−0.34	−1.77	−3.23	−3.62	−3.80	−3.98	−4.70	−3.26	−2.35	−0.92	+0.63
11–12	−1.93	−1.67	−2.81	−3.48	−3.72	−4.13	−4.66	−4.70	−4.03	−3.11	−2.06	−1.52
12–13	−2.95	−2.38	−2.78	−2.65	−2.48	−3.16	−3.93	−3.82	−3.28	−2.46	−2.18	−1.96
13–14	−2.37	−1.74	−1.99	−2.24	−1.53	−1.87	−2.34	−2.19	−1.49	−1.11	−1.27	−1.61
14–15	−1.69	−0.82	−0.84	−1.29	−0.54	−0.46	−0.52	−0.13	−0.03	+0.20	−0.40	−0.79
15–16	−0.18	+0.16	+0.25	−0.11	+0.49	+0.77	+0.92	+1.16	+1.02	+0.42	+0.12	−0.16
16–17	+0.89	+0.69	+0.91	+0.91	+0.97	+1.44	+1.76	+1.46	+0.96	+0.43	+0.44	+0.55
17–18	+1.01	+0.80	+0.89	+1.50	+1.13	+1.41	+1.72	+1.27	+0.40	+0.36	+0.83	+1.00
18–19	+0.77	+0.85	+0.85	+1.09	+0.77	+0.77	+1.10	+0.26	+0.14	+0.68	+0.83	+0.83
19–20	+0.73	+0.74	+0.64	+0.60	+0.25	+0.21	+0.17	+0.09	+0.24	+0.51	+0.62	+0.67
20–21	+0.58	+0.60	+0.50	+0.32	+0.21	−0.08	+0.06	+0.24	+0.25	+0.33	+0.40	+0.24
21–22	+0.30	+0.32	+0.23	+0.12	+0.13	+0.01	+0.21	+0.28	+0.11	+0.09	+0.38	+0.14
22–23	0.00	+0.18	+0.17	+0.02	+0.08	+0.13	+0.32	+0.19	+0.05	+0.02	−0.03	−0.10
23–24	−0.27	−0.05	−0.05	−0.01	+0.12	+0.16	+0.11	+0.11	−0.04	−0.14	−0.16	−0.31
Range.....	5.69	3.89	5.36	6.92	6.62	6.93	7.72	8.95	7.60	5.92	4.05	3.81
Sunspot No.	50.2	56.1	49.5	53.3	54.9	57.6	60.7	61.6	53.1	53.9	53.5	50.9

TABLE 8—*Eleven-year monthly means of diurnal variation eastward earth-current gradient in millivolts per [kilo]meter, Tucson, Arizona, for ten calmest days in each month, 1932-42*

(Tabular values are average departures from mean of day of 60-minute means centering on the half-[hour,] a positive sign indicating current flowing eastward is greater than the mean of day.)

105° west M. M. T. hour	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
00–01	−0.39	−0.50	−0.57	−0.47	−0.44	−0.44	−0.44	−0.28	−0.43	−0.39	−0.39	−0.14
01–02	−0.37	−0.54	−0.56	−0.24	−0.39	−0.20	−0.20	−0.35	−0.30	−0.53	−0.47	−0.25
02–03	−0.41	−0.45	−0.52	−0.35	−0.14	−0.05	−0.28	−0.27	−0.30	−0.49	−0.48	−0.28
03–04	−0.48	−0.34	−0.38	−0.11	+0.05	+0.14	+0.10	−0.07	−0.06	−0.50	−0.41	−0.36
04–05	−0.48	−0.36	−0.24	−0.13	+0.10	−0.01	+0.02	+0.09	−0.16	−0.30	−0.43	−0.33
05–06	−0.33	−0.14	+0.05	0.00	+0.01	−0.05	−0.04	+0.12	−0.28	+0.04	−0.11	−0.27
06–07	−0.38	+0.02	+0.47	+0.59	+0.71	+0.72	+0.67	+1.21	+1.48	+1.03	+0.17	−0.19
07–08	+0.10	+0.14	+1.21	+2.10	+1.84	+1.72	+1.81	+2.90	+2.98	+1.84	+0.87	−0.10
08–09	+1.21	+0.57	+1.26	+1.78	+1.36	+0.95	+1.54	+2.23	+2.35	+2.04	+1.26	+0.62
09–10	+2.58	+1.06	+0.16	+0.55	−0.27	−0.76	−0.34	−0.20	+0.63	+0.73	+1.24	+1.51
10–11	+3.22	+1.01	−0.45	−0.42	−1.16	−1.66	−1.67	−1.52	−0.93	−0.29	+0.98	+1.91
11–12	+1.60	+0.73	−0.35	−0.64	−1.27	−1.65	−1.93	−1.90	−1.84	−0.95	+0.05	+1.28
12–13	−0.53	−0.29	−0.13	−0.75	−1.14	−0.97	−1.56	−1.60	−1.72	−1.08	−0.61	+0.07
13–14	−1.94	−0.68	−0.41	−1.00	−0.38	−0.37	−0.64	−0.88	−0.93	−0.68	−0.73	−0.88
14–15	−2.47	−0.71	−0.60	−0.80	+0.15	+0.51	+0.37	0.00	−0.58	−0.37	−0.81	−1.23
15–16	−1.69	−0.45	−0.34	−0.66	+0.54	+1.14	+1.15	+0.35	−0.16	−0.34	−0.90	−1.27
16–17	−0.56	−0.17	+0.16	−0.07	+0.68	+1.13	+1.52	+0.64	−0.04	−0.07	−0.52	−0.81
17–18	+0.18	+0.24	+0.44	+0.59	+0.61	+0.75	+1.04	+0.35	+0.05	−0.02	−0.09	−0.23
18–19	+0.07	+0.22	+0.51	+0.44	+0.12	+0.13	+0.24	−0.12	−0.16	+0.08	+0.15	+0.08
19–20	+0.31	+0.30	+0.40	+0.12	+0.02	−0.15	−0.30	−0.24	−0.12	+0.21	+0.21	+0.32
20–21	+0.30	+0.36	0.00	−0.04	−0.01	−0.20	−0.13	−0.01	−0.10	+0.16	+0.26	+0.23
21–22	+0.28	+0.23	+0.16	−0.07	−0.30	−0.16	−0.28	−0.02	−0.06	+0.14	+0.36	+0.23
22–23	+0.19	+0.09	+0.02	−0.25	−0.36	−0.16	−0.06	+0.01	−0.15	−0.08	+0.13	+0.12
23–24	−0.07	−0.08	−0.23	−0.36	−0.36	−0.34	−0.33	−0.25	−0.02	−0.22	0.00	−0.09
Range.....	5.69	1.77	1.86	3.10	3.11	3.38	3.74	4.80	4.82	3.12	2.16	3.18
Sunspot No.	50.2	56.1	49.5	53.3	54.9	57.6	60.7	61.6	53.1	53.9	53.5	50.9

variations of the magnetic elements pass from higher latitude to equatorial type as the centers of the circulatory current-systems in the ionized layers of the upper atmosphere are alternately north (summer) and south (winter) of a given station. For this reason the seasonal changes in earth-current flow are also much more complex and less readily described and evaluated.

If the northward component alone is considered, the seasonal change is fairly simple except for a marked increase in amplitude during January. Neglecting this, the seasonal change consists of a large increase in amplitude and a slight advance in the time of maximum flow with increasing height of Sun, and a corresponding decrease and retardation during the winter. The behaviour of the eastward component is distinctly different. For this component the changes in amplitude are small and irregular and the most pronounced feature of the seasonal variation is a large shift in phase which amounts practically to a reversal in direction from winter to summer. Hence, to show the seasonal variation adequately, it is is necessary to construct monthly hodograms to bring out the changes in the amplitude- and phase-relationships of the two components, or harmonic dials which indicate the changes in the more prominent harmonics of the diurnal-variation curves. Such hodograms and dials covering the first three years of recording were given in reference [2], and, since these have been found to be typical, they are not repeated here. Hodograms for the complete period can be readily constructed from the data in Tables 5 to 8. In Table 9 constants of the harmonic series $c_n \sin (n\theta + \phi_n)$ are given for each month of the year. The dials can be readily constructed from them.

In addition to the gradual changes in the relation of phase and amplitude between the two components, which result in three distinct types of current-flow hodograms for winter, summer, and equinoctial periods, the records at Tucson also show two rather brief and anomalous changes which have been repeated each year with great consistency. The first of these consists of a large increase in the amplitude of both components in January. This occurs without affecting the phase-relationship between them which maintains its regular winter character. As a result the amplitude of the eastward component attains its maximum value for the year during January, a fact quite out of line with general theory on the relationship between activity and position of the Sun. The increase in amplitude of the northward component is equally great, but since it is superimposed on a much larger overall seasonal change, it is less effective in distorting the general trend. The second anomaly occurs in March and is confined to the eastward component which becomes quite unusually small and irregular so that the hodogram approaches an irregular but nearly straight line.

In trying to fix on the causes of these unusual seasonal changes it is natural to suspect first that they may be due to the physical characteristics of the region. Changes in the resistance of the current-path, either by reason of seasonal variation in the resistivity of the ground, or by a shift in the position occupied by the earth-current whorls in a non-homogeneous geological structure, might possibly give rise to some of the variations observed. This could only be possible if the changes in

Table 9—*Fourier analysis of monthly means of diurnal variations of earth-current gradients, Tucson, Arizona, for ten camlest days in each month during 11-year period, 1932-42*

Component	Month	Amplitudes				Phase-angles			
		c_1	c_2	c_3	c_4	ϕ_1	ϕ_2	ϕ_3	ϕ_4
		mv/km	mv/km	mv/km	mv/km	°	°	°	°
Northward......	Jan.	0.13	1.32	1.04	0.64	43	217	37	236
	Feb.	0.34	1.04	0.63	0.35	93	235	62	254
	Mar.	0.65	1.38	0.87	0.38	73	251	88	301
	Apr.	1.02	1.73	1.02	0.49	64	260	98	350
	May	0.98	1.65	1.06	0.45	74	274	106	352
	June	0.95	1.74	1.32	0.40	79	280	109	321
	July	1.11	2.08	1.44	0.38	78	270	105	316
	Aug.	1.23	2.12	1.66	0.66	71	274	117	332
	Sep.	0.96	1.64	1.34	0.68	63	271	116	326
	Oct.	0.59	1.27	1.05	0.65	67	261	89	327
	Nov.	0.32	1.09	0.60	0.37	75	245	83	294
	Dec.	0.08	0.98	0.73	0.42	50	226	42	244
	Ann.	0.64	1.37	0.89	0.34	68	258	96	311
Eastward......	Jan.	0.50	1.23	0.94	0.58	332	174	347	174
	Feb.	0.20	0.58	0.27	0.21	282	184	343	181
	Mar.	0.12	0.60	0.19	0.13	297	225	90	12
	Apr.	0.34	0.79	0.41	0.22	354	228	64	343
	May	0.11	0.73	0.55	0.33	300	267	101	314
	June	0.09	0.79	0.69	0.34	134	286	109	310
	July	0.09	0.91	0.86	0.35	72	277	98	301
	Aug.	0.38	0.93	0.89	0.45	20	253	106	301
	Sep.	0.54	1.00	0.64	0.50	10	232	90	315
	Oct.	0.34	0.81	0.49	0.32	347	221	95	316
	Nov.	0.28	0.77	0.24	0.11	336	187	23	244
	Dec.	0.33	0.82	0.54	0.24	325	161	330	161
	Ann.	0.23	0.64	0.37	0.15	348	224	74	294

resistivity, the shift in position, and the complexity of the area were sufficiently great. Opposed to such an explanation is the fact that resistivity-surveys made at a number of widely separated stations have shown that the seasonal changes which occur in the specific resistance of earth-materials are confined to a superficial surface-layer, so shallow that the average values, where any considerable depth is considered, do not change appreciably during the year. Hence resistivity-changes in a given current path are pretty well ruled out as a possible cause. There is, moreover, no indication that the structure of the region about Tucson is unusually complex. For this reason unusual changes in the resistance of the current-path would not be expected if its position shifts under the influence of shifts in the currents in the upper atmosphere.

Looking at the problem from another viewpoint, an examination of the early records [2] has shown that, paralleling all the peculiar features noted in the seasonal variation in earth-current flow at Tucson, similar unusual changes are found in the records of the magnetic elements as obtained at that station. It would therefore appear that the changes here described are not merely peculiarities of the earth-current records alone,

but that they are connected with, and caused, by variations in the processes responsible for the diurnal variations in the Earth's magnetic field and for the accompanying flow of induced currents in the Earth. An intensive and detailed study of the earth-current records in comparison with those of the magnetic field may consequently prove fruitful in establishing more definitely the character of the mechanisms involved in the seasonal and diurnal variations of both. Such study is proposed as soon as the complete magnetic records for this sunspot-cycle are available.

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[2] Terr. Mag., **40**, 183-192 (1935).
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[4] Trans. Washington Meeting, 1939; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 11, 467-473 (1940).

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Washington 15, D. C., July 29, 1944

LETTERS TO EDITOR

(See also page 207)

PROVISIONAL SUNSPOT-NUMBERS FOR APRIL TO MAY, 1944

(Dependent alone on observation at Zürich Observatory)

Day	April	May
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0*
7	0	0*
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0*
16	0	0*
17	0	0*
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0
28	0	11
29	0	12
30	0	W 23[c]
31	0	16
Means......	0.0	2.2
No. days....	30	31

*Observed at Locarno.
[a]Passage of an average-sized group through the central meridian.
[b]Passage of a large group or spot through the central meridian.
[c]New formation of a group developing into a middle-sized or large center of activity: *E*, on the eastern part of the Sun's disk; *W*, on the western part; *M*, in the central-circle zone.
[d]Entrance of a large or average-sized center of activity on the east limb.

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W. BRUNNER

EVALUATION AND INTERPRETATION OF THE COLUMNAR RESISTANCE OF THE ATMOSPHERE

By O. H. Gish

The term columnar resistance is used by the writer instead of the more explicit but unwieldy phrase, namely: The electrical resistance of a vertical column of atmosphere having unit cross-sectional area and extending from the Earth's surface to a specified altitude. This term and the conception, which it denotes, facilitate the discussion and interpretation of some aspects of atmospheric electricity. For example, the observation that the density of the electric current, which flows from air to earth in fair weather, is on the average, considerably smaller in the vicinity of large cities than over open country or over the oceans, may be attributed to a greater columnar resistance of the atmosphere over urban areas—a fourfold to fivefold increase is indicated for some places. Some impurities introduced into the air in various ways, such as by the burning of coal or other substances, increase the resistivity of the air thus polluted. The corresponding increase in columnar resistance may be regarded as equal to the increase of resistivity in the aggregate, throughout a vertical column and therefore depends upon the degree of pollution and upon the vertical distribution of the impurities. Such interpretations are so satisfactory in their qualitative aspects that one is encouraged to make quantitative estimates of some features. For example, one may attempt to estimate the altitude to which a given distribution of impurities must extend from the surface in order to effect an indicated change in columnar resistance. Doubtless, estimates of this character have been made in the past by other investigators who, like the writer, heretofore rated them too immature for publication.

Although some such estimates shall be reported here, by way of example, the chief purpose of this paper is: (*a*) To state conditions which must be satisfied for the concept columnar resistance to be applicable; (*b*) to outline methods of evaluating and analyzing columnar resistance; and (*c*) to suggest some possible interpretations of contrasts or variations in the values thus obtained. A careful scrutiny of assumptions usually accepted in discussions of atmospheric electricity is required because some interesting variations of columnar resistance, which are consistently indicated by observed data, are relatively small.

Definition and assumptions—The columnar resistance (R) may be defined as the integral, along the vertical, of the air-resistivity (γ) from the Earth's surface to a specified altitude. This definition, and the indicated method for evaluating R, has significance for the cases in hand provided (*a*) the vertical component of electric current is wholly a conduction-current and (*b*) the density of the vertical component of current (i_z) is independent of altitude. If these circumstances obtain one may write

$$i_z = (E_z/\gamma) = \left(\int_0^h E_z \mathrm{d}z \Big/ \int_0^h \gamma\, \mathrm{d}z\right) = (V_h/R_h) \qquad (1)$$

where E_z is the component of the potential-gradient along the vertical (z) and V_h is the potential relative to the Earth at an altitude h. The proviso stated above is of course never fully realized in the atmosphere. When wind and gravity or other mechanical forces produce electric convection-currents, such as are prominent in thunder-storms or when the electric field suffers rapid change and displacement-currents become appreciable, the relations in (1) do not hold. But in fair weather they are doubtless valid, to within a fair approximation, for average circumstances. Displacement-currents and the more prominent convection-currents vary from the upward to the downward sense in relatively short intervals of time and accordingly leave little trace in the mean values of the measured air-earth current-density. It is implied in the general conditions stated above that both the air-conductivity (or its reciprocal, the resistivity) and the electric space-charge density (ρ) must not be distributed in a lumpy manner although each may vary as a function of altitude provided ρ is proportional to $(d\gamma/dz)$. The assumption that the displacement-current is negligibly small also implies that the temporal variation in space-charge, $(\partial\rho/\partial t)$, is negligible.

Most of these conditions are certainly violated in and about thunder-storms. There large local concentrations of electricity are continuously built up by the action of wind and gravity, electric charge is transported on rain-drops or snow-crystals, rising in ascending air-currents or falling under the action of wind and gravity, and in general the electric state and properties of the atmosphere undergo large and rapid changes.

Compliance with the specified conditions is much more likely in fair weather, but one cannot be assured that this is always adequate. An irregular or lumpy distribution of conductivity or of space-charge or of both is frequently indicated in fair weather. This condition appears to be more prominent in the lower atmosphere, within some tens of meters from the Earth's surface, and at least in some cases is associated with wind-velocity and air-turbulence. Accordingly, at a given instant and place one or the other or both of the fundamental requirements is violated in some degree. If the lumpy distribution occurs in non-turbulent air, the vertical component of electric current is wholly a conduction-current, but it is not independent of altitude—an increase with altitude at one place is associated with a corresponding decrease at another place. In case the air is turbulent, electric charge may be carried successively upward and downward in the eddies of air. Such convection-currents indirectly introduce a variation with altitude in the vertical conduction-current because the net current tends to remain constant. In both these cases traces of the objectionable effects are doubtless negligible in the means of a large number of measurements. A contribution to electric convection, that would not be eliminated in the average, may be made by eddy-diffusion, but no definite evidence that this is appreciable under normal fair-weather conditions has thus far been reported [see 1 of "References" at end of paper]. During heavy rains the convection-current density, estimated from the net charge of the rain and the rate of rainfall, is sometimes five orders of magnitude greater than the normal conduction-current. In such circumstances the vertical conduction-current can scarcely be independent of altitude. Variations of as much as two orders of magnitude are sometimes indicated by the temporal variations observed at the surface.

That the average vertical conduction-current in fair weather is essentially independent of altitude seems to be indicated by some measurements made on balloon flights, the only exception being results reported by Everling and Wigand [2]. That exception is, however, not significant. Variations both with time and with geographical position of the drifting balloon are doubtless involved; also no acceptable explanation of the departure has been found [1]. It should also be noted here that the space-charge density in fair weather diminishes rapidly with altitude. Accordingly, except near the surface, $(\partial\rho/\partial t)$ and $(\partial\rho/\partial z)$ are both small and consequently the divergence of the conduction-current must be small. Observations reveal no evidence of a persistent dependence of the vertical conduction-current [3] upon altitude within a few meters from the ground even though this is the region where electric convection and temporal changes in space-charge are most likely to contribute to such a dependence in fair weather.

The displacement-current $(1/4\pi)(\partial E/\partial t)$ as indicated by observations made near the Earth's surface, although usually negligible in the average, is appreciable in some cases. For example, the typical diurnal variation of potential-gradient at the Huancayo Magnetic Observatory during the dry season decreases so rapidly between 06^h and 08^h that the average displacement-current amounts to about five per cent of the vertical conduction-current for a period of about an hour.

Another conception which is employed when considering some aspects of atmospheric electricity is that the Earth may be regarded as a perfectly conducting sphere which is surrounded by another "perfect" conductor, thus simulating a spherical condenser. The validity of the first part of this assumption is attested by the fact that even for the higher observed values of earth-resistivity a free electric charge placed at a point on the Earth's surface would, after the lapse of a small fraction of a second, be practically uniformly distributed over the surface. For example, the relaxation-time for the best Italian marble is less than 0.01 second, whereas that of air adjacent to the Earth is about 400 seconds. Accordingly, the Earth's surface would be essentially an equipotential surface except momentarily in the vicinity of a lightning-discharge or other transient electric phenomenon. Appreciable departures from an equipotential surfaec also may occur over areas where electric currents, generated in the Earth, traverse the boundary between a good conductor and a poor conductor, but a rough estimate indicates that these are doubtless too small to be detected by methods usually employed in measuring the electric field in the atmosphere.

The justification for regarding some portion of the high atmosphere as a good conductor completely surrounding the Earth, thus serving as the outer element of a spherical condenser-model, depends upon several lines of evidence. The fact that an important component of the diurnal variation of potential-gradient varies as a function of universal time provides indirect evidence. Geomagnetic phenomena and effects observed in radio transmission indicate that the E-layer of the ionosphere is a sufficiently good conductor, both in daytime and at night, to satisfy this condition. It apparently also completely surrounds the Earth. But there are reasons for thinking that the effective outer element of the condenser-model is provided by the atmosphere at a considerably lower level. For example, most of those who have investigated the ques-

tion think there is no conclusive evidence of a significant correlation between changes of any atmospheric-electric element, observed at the Earth's surface, and those manifestations of northern lights or phases of terrestrial electromagnetic phenomena or those features of radio transmission, which are associated with large changes of ionization at levels in or below the E-layer—levels ranging in altitude from 60 to 100 km. Such a correlation is to be expected unless a lower stratum of the atmosphere serves as an electrostatic shield for the Earth. The reports of those who adduced evidence for such a correlation are reviewed by the writer in a previous paper [Trans. Amer. Geophys. Union, 12th annual meeting, 140-142 (1931)]. Since that review F. L. Cooper [Physics, **7**, 387-394 (1936), and Amer. J. Sci., **240**, 584-593 (1942)] reports that large changes in potential-gradient occur at about the time a sunspot crosses "a plane through the axis of the Sun and the Earth," and that these changes have a tendency to recur at 27-day intervals. The writer was astonished by this claim as doubtless were other investigators who had looked for evidence of a correlation between prominent changes of potential-gradient and sunspot-activity and had found none. Maybe it will eventually be found that some of the small changes, doubtless less than a departure of ten per cent from normal, are correlated with sunspot-activity, magnetic activity, etc., but anyone who has compared the electrograms from several observatories for a period of years is certainly convinced that a careful statistical study will be required to reveal such effects if they exist, and that there is no chance of finding corroboration for the claims made by Cooper.

It would seem that atmospheric-electric elements are more likely to be correlated with bright chromospheric eruptions than with other manifestations of solar activity, because the correspondence between these eruptions and effects in geomagnetism, in geoelectricity, and in radio transmission is remarkable in being so close. Moreover, the character of these effects indicates rather definitely that the ionizing radiation from the eruptions is effective at levels considerably below the E-layer. But no such correlation was found in a search made independently by the writer and his associates Wait and Torreson [4], although departures as great as five per cent of the normal value of any of the elements—potential-gradient, positive, or negative conductivity—could doubtless have been detected.

No measure of the air-conductivity in the altitude-range from 22 to about 60 km has yet been obtained but at an altitude of 20 km it is about 100 times that of air at sea-level, as was shown by measurements made on the flight of the stratosphere balloon *Explorer II* [5]. Accordingly, the net electric charge of a body of air at that level in the atmosphere would decrease at a rate of about 25 per cent per second and, after a lapse of some tens of seconds, the charge-density would be relatively insignificant.

The air-conductivity doubtless increases with altitude in the electrically unexplored region from 20 km up to near the E-layer of the ionosphere (the relaxation-time decreasing in a corresponding manner) so that somewhere in this region, if not at a lower altitude, the potential (V) relative to the Earth is essentially the same in all geographical positions at a given instant during a steady electric state. No persistent departures from this condition in the high atmosphere have been definitely detected, although Gish and Sherman [6] present some evidence

which may indicate a local departure. Transient departures are of course to be expected, especially in the vicinity of thunder-storms, but it is not known how far from the active center, especially in the vertical direction, these have significance for this discussion.

The published data by C. T. R. Wilson [7], Schonland and Craib [8], which might be expected to give some indication of the latter, are, however, not suitable for the purpose because the field-strengths and field-changes of the smaller magnitude required were not recorded, and the distance of the observer from the more remote storms could not be ascertained. Those data are interpreted largely in terms of the simple bipolar cloud-model which does not take account of electrical conditions in the higher atmosphere. A more comprehensive program of observation and analysis is required in order to obtain the desired information. A move in that direction has been started by Workman and Holzer [9] but the brief report on that work [10] does not provide data of the kind required here. Some simple observations, however, do seem to demand consideration of the state of the higher atmosphere. An interesting example follows.

Sudden field-changes of from 10 to 20 volts per meter in the vertical component of the electric field were observed by K. L. Sherman and the writer while using the Simpson stretched-wire method for measuring potential-gradient on an elevated plateau (4,000 feet or about 1,200 m) in the Black Hills of South Dakota, on the afternoon of a day with a remarkably clear sky in June, 1935. Each such field-change was finally observed to coincide with a faint glow which appeared over the northern horizon, where later the top of a thunder-head became just visible. Apparently this was a local convectional thunder-storm so far away (say about 100 miles) that field-changes of the magnitude observed could not be attributed to any of the simpler electrical models of the thunder-storm (for example the bipolar type). Similar effects appear on the grams of potential-gradient obtained at the Huancayo Magnetic Observatory (altitude about 11,000 feet or 3,300 meters, where frequently on days when no thunder-clouds are observed the potential-gradient is disturbed during that period of the afternoon in which local thunder-storms usually occur.

These effects are thought to be attributable to an electric charge-distribution in the higher atmosphere. That charge is "bound" to the charge in the cloud prior to the discharge of the latter, but immediately after at least a part is free to establish a field-component over a considerable area about the storm-center. This field-component diminishes with time as the high-altitude space-charge is dispersed, or neutralized in some manner. No reports by other investigators of comparable field-changes at such great distances are known to the writer. Perhaps phenomena of this sort are dependent upon special circumstances—they may be more pronounced at high-altitude stations. The bearing of this upon the subject in hand is that these observations may indicate departures from a constant potential at a given instant in the high atmosphere which may occasionally be quite appreciable within a radius of perhaps 200 km from the center of a thunder-storm. The rate of decay of these field-changes corresponds to that for a charge at an altitude of not more than 10 to 20 km in the atmosphere.

Methods of estimating columnar resistance—Estimates of columnar resistance have been made by the following methods: (*a*) The difference of

potential (V) between the Earth and the high atmosphere—estimated from measurements of potential-gradient, made on balloon flights—was divided by a representative value for the vertical conduction-current (i), that is, $R=(V/i)$. (*b*) The integral of air-resistivity (γ) from the Earth's surface to an altitude of 18 km was calculated from values of air-conductivity registered on the flight of the stratosphere balloon *Explorer II*, namely, $R=\int_0^{18\text{km}}\gamma\, dz$. (*c*) The integral of air-resistivity from the Earth's surface to an altitude of about 25 km was based on measured values of cosmic-radiation intensity and representative meteorological data. (*d*) Relative values of columnar resistance have been obtained by comparing values of the electric conduction-current. The columnar resistance (R) for a position on land in terms of that (R_0) of a representative ocean position, namely $(R/R_0)=(i_0/i)$, is of particular interest.

Estimates made by the first method are probably the least reliable. Since the measurements of potential-gradient were all made at altitudes less than ten km, most of them at altitudes below six km, extrapolation to higher altitudes is required. Schweidler's summary of means [11] of the available data can be represented by the empirical expression $E=[0.9\exp(-3.5z)+0.4\exp(-0.23z)]$ where z is the altitude in km and E is the gradient in volts/cm. The integral of this from $z=0$ to $z=\infty$ gives 200,000 volts for the value of V, but if the upper limit of integration is taken as nine km (about the highest altitude for which data are available) one obtains $V=178{,}000$ volts. This comparison indicates that the error from extrapolation may be quite small provided the available data are representative. The accuracy of estimates by this method also depends upon the value selected for i. Since values for i which correspond in time and position with the measurements of gradient are not available, one may try a mean of values reported from central European stations, located in the general region where the balloon flights were made. For such a value of i (6×10^{-7} esu/cm^2) or (2×10^{-16} amp cm^2) and the estimated value of V (200,000 volts), $R=10^{21}$ ohms.

The original estimate of R by the second method [5] is close to this value. In that estimate, however, it was necessary to extrapolate for values of γ (or λ) from an altitude of about 600 meters to sea-level. Re-examination of this extrapolation gives indication that a better estimate may be about 80 per cent of this.

Estimates of R by the third method [12] are smaller than those which have just been mentioned. These were made primarily to ascertain whether and to what extent the columnar resistance depends upon latitude. Such a dependence was expected after observations of cosmic radiation revealed that not only is the intensity of that radiation at sea-level less in low than in high latitudes, but also that the latitude-effect at higher levels is more pronounced than at sea-leavel. These estimates indicated that R near the equator is about 24 per cent greater than that at magnetic latitude 50°, a result which is consistent with the latitude-effect in potential-gradient, first noted by Mauchly [13] in data measured over the oceans, and which provides a quantitative explanation of his observations. That explanation depends upon the following considerations: The relation between R_1 and R_2 for two latitudes is $(R_1/R_2)=(V_1i_2/V_2i_1)$. But if $V_1=V_2$ then $(R_1/R_2)=(i_2/i_1)=(E_2\gamma_1/E_1\gamma_2)$. Now

the observations at sea show no appreciable dependence of γ upon latitude—a result that is also consistent with calculations which take into account the latitudinal distribution near the Earth's surface of cosmic-radiation intensity and of representative air-temperature and pressure. Hence $(R_1/R_2) \doteq (E_2/E_1)$, where E_1 and E_2 represent the potential-gradient at sea-level for the respective latitudes. The calculated values of R and the observed values of E satisfy this equation.

Estimates of R made by the third method are thought to be a fair approximation to actual values over the open ocean, but they are doubtless somewhat too small owing to the fact that account could not be taken of the nuclei of condensation which appreciably increase the air-resistivity even over open ocean. This increase of resistivity at sea-level is estimated to be not more than 95 per cent and not less than 45 per cent. But the concentration of nuclei, and the corresponding enhancement of resistivity, doubtless decrease with altitude and consequently the disparity between the actual and the estimated values of R would be smaller than may be inferred from the foregoing statement.

Measurements made on balloon flights [14] of the concentration of nuclei in the air may, in the average, be represented by the empirical equation $N=[49{,}000 \exp(-2.46z)+850 \exp(-0.53z)]$, where z is altitude in km. If the nuclei-concentration over the oceans decreases with altitude in this manner, then it is estimated that the enhanced columnar resistance (R') exceeds that calculated (R) by less than nine per cent. The basis for the estimate of the relative disparity $[(R'-R)/R]$, is as follows.

The relation between the concentration of small ions (n') and the nuclei concentration (N), when small-ion pairs are formed at the rate of q per cc per sec, is taken to be $q=(\alpha n_1'n_2'+\beta n_1'N)$. The value 1.6×10^{-6} is used for the constant α—the larger value, 2×10^{-6} indicated by some measurements made in the laboratory, would give a more favorable result. The value of the constant β can be determined from this equilibrium-relation by substituting values of q, of n_1' and n_2' (positive and negative ion-concentration, respectively) and of N observed at sea. But βN is determined instead because fewer observations of N than of the other elements are available and because β and N appear only in the combination βN, in the expression for air-resistivity and in that for columnar-resistance, as a function of altitude.

If it is assumed that $n_1'=n_2'=n'$, which is doubtless admissible except within a few meters from the Earth's surface, then from the equilibrium-relation, one obtains

$$n'=\sqrt{q/\alpha}[\sqrt{1+B^2}-B] \tag{2}$$

where $B=\beta N/2\sqrt{\alpha q}$. Now $\sqrt{q/\alpha}=n$, the small-ion concentration when no nuclei are present and since the air-resistivity is inversely proportional to ion-concentration

$$(\gamma'/\gamma)=(\sqrt{1+B^2}+B) \tag{3}$$

The value of B for average conditions at sea ($n_1=600$, $n_2=500$ ions/cc, and $q\leqslant 2$ ion-pairs per cc per sec) as determined from the relation $B=[(q-\alpha n_1n_2)/(2n_1\sqrt{\alpha q})]$ is about 0.7. The value of B would be smaller if a larger value of α or a smaller value of q were used but the values used

here are those which give an estimate for B, and accordingly for $[(\gamma'-\gamma)/\gamma]$, which is as large as seems admissible.

For the estimated maximum value of B, an approximate expression for the relative increase in resistivity at the surface over open ocean is

$$[(\gamma'-\gamma)/\gamma]=B[1+(B/2)-(B^3/8)+(B^5/16)]=F(B) \quad (4)$$

This gives a value which exceeds that (0.936) calculated from equation (3) by less than 0.5 per cent.

Now if the concentration of nuclei at sea varies with altitude in the manner indicated by Wigand's data, then

$$B=[\beta N_0/(2\sqrt{\alpha q})]\,[0.983 \exp(-2.46z)+0.017 \exp(-0.53z)] \quad (5)$$

The value of B decreases with altitude not only because of the decrease in N but also because, over the oceans, q increases and $(\beta/\sqrt{\alpha})$ may decrease somewhat with altitude, but the decrease at the lower altitudes depends on the decrease in N, hence for simplicity it is assumed, in the following that $(\beta/\sqrt{\alpha q})$ is independent of altitude. The overestimate of the enhancement of the columnar resistance, attributable to this assumption, probably increases the factor of safety in the estimate.

The increase in columnar resistance then is

$$(R'-R)=\int_0^\infty F(B)\gamma dz \quad (6)$$

The values of γ from the Earth's surface to an altitude of 25 km may apparently be accurately expressed by an empirical expression of the form

$$\gamma=H\exp(-bz)+G\exp(-cz) \quad (7)$$

The values of the constants, which are appropriate for the calculations reported by Gish and Sherman [5, 12] and for z expressed in km are given in Table 1.

TABLE 1

Magnetic latitude	H	G	b	c
°	10^{15} *ohm-cm*	10^{15} *ohm-cm*		
50	1.387	0.369	0.375	0.121
0	1.253	0.545	0.432	0.100

Substituting this expression for γ and the explicit expression for $F(B)$ (4) in (6), the value of $(R'-R)$ may be evaluated. The value of $[(R'-R)/R]$ for latitude 50° over open ocean, estimated in this way, is 0.08. A value of 0.04 is obtained if B is taken as 0.38—the smallest admissible value, in the opinion of the writer.

The reliability of this estimate is thought to depend almost entirely upon the validity of the assumed vertical distribution of nuclei. The observations of nuclei were made over land where the vertical distribution may differ from that over open ocean because over land some of the sources of nuclei are restricted in area. The dispersion of nuclei from such sources doubtless gives rise to a vertical distribution which differs, in the average,

from that which would be found when, as over the ocean, the source is probably rather uniformly distributed over an extensive area. Furthermore, the character of the surface—its roughness—plays a rôle. What differences, between land and sea, in the vertical distribution of nuclei may be attributed to these sources? No entirely satisfactory answer to this question is known, but it seems likely that the average decrease of nuclei-concentrations with altitude is generally greater at sea than on land.

Another estimate of the average increase of columnar resistance, attributable to the distribution of nuclei of condensation in the lower atmosphere, seems worth mention here. Since the potential-gradient divided by the air-resistivity at a given level in the atmosphere is independent of altitude, under conditions assumed here, the variation of gradient with altitude in air free from nuclei should be given by equation (7) multiplied by an appropriate value of the vertical conduction-current. The observed values for gradient, as summarized by Schweidler, however, vary with altitude in a manner different from that for the resistivity calculated for about the same magnetic latitude (50°). This fact may be ascribed to the presence of nuclei, and the corresponding increase in resistivity, in the atmosphere where the observations of gradient were made. But the data for potential-gradient versus altitude are closely represented by the following empirical expression

$$E=[81.8\exp(-4.52z)+38.6\exp(-0.375z)+10.27\exp(-0.121z)] \quad (8)$$

where E represents the gradient in volts/meter and z the altitude in km. The exponents of the last two terms on the right-hand side of equation (8) are the same as those of the exponential terms in equation (7). If the air-earth current-density is taken equal to 8.35×10^{-7} esu/cm^2, expressions for resistivity and of columnar resistance as a function of altitude may be derived. The expressions thus obtained are consistent with the observations of potential-gradient, and with the view that (*a*) fundamentally the resistivity varies with altitude in the manner indicated by equation (7) if numerical values for latitude 50° north are used, and (*b*) owing to the presence of nuclei the resistivity is increased at lower levels. This increase can be expressed by an additional exponential term with $-4.52z$ as exponent. The expression for resistivity obtained in this way is

$$\gamma=[2.94\exp(-4.52z)+1.39\exp(-0.375z)+0.369\exp(-0.121z)] \times10^{15}\text{ohm-cm} \quad (9)$$

On this view one would conclude that owing to the presence of nuclei in the lower atmosphere: (*a*) The resistivity at the Earth's surface was about three times that which would have obtained if there had been no nuclei in the air; (*b*) that at an altitude of one km the excess of resistivity, owing to the presence of nuclei, was only one per cent of that at the surface; (*c*) the indicated decrease with altitude in this effect is somewhat greater than would be inferred from the observed vertical distribution of nuclei; (*d*) this decrease is such that despite the large indicated resistivity at the surface, the columnar resistance, calculated from the empirical expression, is not much greater than the maximum, estimated earlier in this report for the open ocean.

The chief significance of this comparison is that it indicates a reasonably satisfactory quantitative relation between the observations of

gradient, of cosmic-radiation intensity, and of nuclei-concentration at a given level in the atmosphere, and illustrates a method, with a reasonable physical basis, of analysis and interpretation of such data.

The data used in this case could at best represent average conditions only in a rough way, and the possible interpretations listed above, although consistent in qualitative aspects with other observations, can be regarded as only tentative.

It is scarcely to be expected that the component of resistivity, attributable to the presence of nuclei always decreases with altitude in the manner and at the rate indicated by the foregoing comparisons. Certainly in the vicinity of cities, or other areas where nuclei are abundantly supplied to the atmosphere, a smoke-stream with its nuclei rises from the city, flows with the wind, and spreads away from the axis of the smoke-stream. In such circumstances the concentration of nuclei and the air-resistivity would increase with altitude, for some distance from the source, reach a maximum, and then decrease with further increase in altitude.

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A SURVEY OF METHODS OF CONSTRUCTING MAGNETIC CHARTS

By Arthur Bernstein

Introduction

This survey of some of the literature on methods of representing the distribution of magnetic phenomena over the Earth's surface was undertaken primarily to provide a background for a study of the problem of improvement of methods of constructing world magnetic charts. In every case what was sought was a description of the method used in locating isomagnetic lines on charts, that is, of the scheme of interpolation used. With few exceptions, works written in English only were examined. Since the number of reports of magnetic surveys which include some description, however meager, of the method of interpolation is quite large, and since the number of different modes of construction is small, relatively few such reports have been abstracted.

It is evident from this short survey that cartographers have not developed a uniform method for constructing magnetic charts, although some 240 years have elapsed since Halley published his famous isomagnetic chart. The tracing of contours is still largely a matter of individual judgment; and in constructing charts for a current epoch the cartographer is often guided in sketching both the general configuration of the curves and their course in detail by charts for past epochs. Thus errors of unknown and perhaps substantial magnitude carry over from epoch to epoch.

Two general procedures have been employed in the tracing of contours. These may be termed (*a*) the analytic and (*b*) the graphic methods. The former, in general, consists of assuming that the contours to be drawn may be approximated with sufficient accuracy by an expression of the form

$$E=E_0+a\triangle\lambda+b\triangle\phi+c(\triangle\lambda)^2+d(\triangle\phi)^2+e(\triangle\lambda)(\triangle\phi)+\ \ldots \qquad (1)$$

where E_0 is the value of the magnetic element at some centrally chosen point, $\triangle\lambda$ and $\triangle\phi$ are departures in longitude and latitude from that point, and a, b, c, d, e, etc., are coefficients to be determined from the observed data—generally by the method of least squares. E is the normal value which is to be determined for the point (λ, ϕ).

The graphic method consists, essentially, of free-hand smoothing by the draftsman, presumably without the aid of any mathematical formula, although certain criteria of smoothing may be observed.

The chief objection to the first or analytic method is its complexity and the labor involved in calculation, especially when the number of stations is large. If relatively simple polynomial approximation not exceeding, say, the third degree, be used, extreme isolated values may not be shown. If it is desired to show such values the device of listing the numerical values on the chart may be used. An advantage of this procedure is that it provides a uniform basis which makes for more valid comparison with other charts.

The graphic method seems to have the advantage of avoiding laborious calculation, but the relative influence of anomalies remains a matter of uneasy judgment for the cartographer.

Three general methods of representing the distribution of magnetism

over the Earth's surface may be noted: (1) Contour-lines—also called "*Halleyan lines*" and "*isolines*"; (2) symbols (circles, squares, etc.) of varying sizes and colors, and with or without accompanying numerical values; and (3) series of graphs for, say, every 5° of latitude, in rectangular or polar coordinates.

The first method is the one almost universally employed at present; the second has been proposed and used, recently, by Ljungdahl [see 2, 3 of "References" at end of paper]; the third is seldom used.

In attempting an adequate representation by any one of these methods it is necessary, first, to find a sufficient number of isopoints over the area for which the representation is intended. This is done at present by interpolating linearly between given points. Essentially this is a problem, however, in two-variable interpolation with unequal intervals of both arguments. Moreover it is a problem in "inverse" interpolation because it is required to determine the values of λ and ϕ for which the function takes on a specified value c. The problem is made more complex by the fact that the set of points $P(\lambda, \phi)$ are not lattice-points of any rectangular net, no pair of the set, in general, lying on a line parallel to either the λ- or ϕ-axis.

In order to solve this problem some assumptions concerning the probable behavior of the magnetic elements being charted must be made to guide the cartographer. Considerations of the use to which a chart will be put help to determine the amount of twistedness (degree of polynomial approximation) to be used. Thus, if every isopoint had to be satisfied exactly, the resulting curves would, in general, be twisted curves of such irregularity as to render the chart useless to most readers; more important, such curves would not necessarily be a more accurate representation of the field.

Early chart construction

In 1701, Edmund Halley published his first isogonic chart for the Atlantic Ocean, epoch 1700, in which the use of isolines to represent the surface-distribution of values of a geophysical element first came into prominence.*

Mountaine and Dodson, who published revisions of Halley's charts for the approximate epochs 1744 and 1756, also appear to have left no account of their methods. As was pointed out by Churchman [24], Halley's charts were not founded entirely on his own observations, and Mountaine and Dodson used observations from many different sources and uncertain locations so that "These charts cannot be expected to be true in every part—" [24, p. xv].

Charts of the Earth—or major portions of it—have since been published from time to time, their accuracy increasing as new and better data became available. A comprehensive list of such charts is given by Hellmann [17, pp. 32 and following]. At the same time, as extensive surveys of selected regions of the Earth's surface were completed and magnetic maps of these selected areas were required, it became desirable

*According to Navarrete [40] Alonzo de Santa Cruz, cosmographer for Charles II of Spain, constructed an isogonic chart in the year 1530, which would antedate Halley by about 170 years. According to Athanasius Kircher, an early writer on magnetism, an isogonic chart was invented by Christopher Burro (also written Borro, Borri, and Bruno) sometime before 1643 [41].

The claims to priority advanced for Burro and Santa Cruz are evaluated by Hellmann, outstanding authority on the history of early magnetic charts [16, pp. 16 and following]. Although Halley was not the first to use the technique of isolines he was the first to undertake the systematic measurement of the declination over a large part of then navigable oceans, to map such data accurately, and to publish them.

to show "normal" contours in which the effects of local disturbances were considerably reduced or eliminated. Such contours would replace the irregular twisted contours which resulted from passing smooth curves through isopoints.

British charts

One of the earliest published applications of what may be called the analytic method of determining isolines may be found in the magnetic map of Ireland, resulting from the survey of that country in 1835, by H. Lloyd [19, 20]. Essentially, Lloyd's method of determination of the isogons was to use a linear approximation of the form given in equation (1).

Sabine [22] used a method developed for him by Archibald Smith for the determination of isodynamics for North America. This method uses the approximation (1) to second-order terms except that $\triangle\lambda$ is replaced by $\triangle\lambda \cos\phi$. Replacing $\triangle\lambda \cos\phi$, in turn, by x, and $\triangle\phi$ by y the approximation becomes

$$E = E_0 + ax + by + cx^2 + dy^2 + exy \qquad (2)$$

Smith chose this form (equation of a family of concentric ellipses in the XY-plane) as the simplest approximation to the oval-shaped curves (on the sphere) which were indicated by the data. He stated that the isomagnetic lines thus fitted consisted of a series of ovals on the sphere, and that these would transform into a system of ellipses under a projection where (1) parallels of latitude transform to equidistant horizontal lines, and (2) parallels of longitude transform to curves which intersect in the projections of the poles, and which are normal to the equator (projected) at distances proportional to the difference between the longitude of each meridian and that of the central meridian; on the other parallels of latitude the distance x of each meridian from the central meridian is equal to the product of the distance on the equator and $\cos\phi$.

This projection resembles the globular [43], except that here the parallels are straight lines and not arcs of circles.

The coordinates x_p, y_p of the common center of ellipses, which is the place of maximum intensity, are found by differentiating (2) with respect to both x and x and solving simultaneously, whence

$$x_p = (be - 2ad)/(4dc - e^2) \qquad y_p = (ae - 2bc)/(4dc - e^2)$$

The value of E at this point is

$$E_p = E_0 + [(abe - da^2 - cb^2)/(4cd - e^2)]$$

The constants a, b, c, d, e were determined by the method of least squares, 82 observation-equations being used. This chart as well as that for the inclination was for epoch 1842-45. The method given by Smith is of special interest because by an extension of it several magnetic charts for the United States were constructed by Schott [10] and Hazard [11].

For the construction of his chart of inclination Sabine found Lloyd's method unsuitable and the calculations too laborious; Sabine's contours were not nearly straight lines. Therefore, he resorted to a graphic method which he had previously employed in tracing isoclinals for Great Britain. This method is described [21, pp. 257 and following] as follows: The

preliminary placement of points (observed values) is made on a Mercator base-map of sufficiently large scale. The isoclinals are then sketched in roughly. Lines are then drawn through each observed point perpendicular to the direction of isoclinals, and distances are set off on these perpendiculars "corresponding to the value in geographical miles of the number of minutes which the observed dip is either above or below the full degree to which it is nearest. The value in geographical miles corresponding to the odd minutes is computed proportionately to the distance between the two isoclinals on either side of the place of observation; and it is set off, from the cross which marked the station, towards the isoclinal of full degree which is nearest the observation." A cross is then made in a different colored ink to mark the spot, which is the revised position through which (or near which if smoothing is required) the line is drawn.

The next large-scale magnetic survey undertaken by the British was in the voyages of H. M. S. *Challenger*. The results were summarized in four world charts, epoch 1880, for H, D, I, and Z. Considerable use was made of data from other sources—some of which are mentioned in the report [25] and some of which are not [25, pp. 6-7]. No discussion of the method used in the construction of chart was found.

In 1884-88, A. W. Rücker and T. E. Thorpe conducted a magnetic survey of Great Britain and Ireland, using 205 stations, mean epoch January 1, 1886; and in 1889-92 they conducted a second survey using 667 different stations, mean epoch January 1, 1891. In their account of the first survey [34, p. 233] they introduced the term "terrestrial line": "If we suppose that a series of magnetic curves are drawn in which all distortions due to local magnetism are neglected, except those which are on a scale comparable with the dimensions of the Earth itself, they would be the *terrestrial isomagnetic lines;* on the other hand lines which showed every disturbance, however large or small, would be the *true isomagnetic lines*. The object of a survey is to determine as nearly as possible the points of the true lines, and to deduce from them the directions of the terrestrial lines in the district under investigation."

The same authors note that "In nothing do different magnetic surveys differ more widely than in the methods employed of drawing these lines (terrestrial isomagnetics). Some observers have calculated them by least squares; others give maps on which they are exhibited, but say nothing about the principles in accordance with which they have been drawn. But inasmuch as the main object and result of a survey is the delineation of these isomagnetics, it seems to us that it is most important that they should be drawn with all the accuracy that the observations will allow."

Descriptive summaries of their method of deriving their terrestrial isomagnetics may be found in an article by Rücker [35], and in the article by Chree [32] as well as in [34]. Briefly stated, they broke up the area surveyed into nine overlapping districts. For each district an arithmetic mean of the values of latitude, longitude, and magnetic element of all stations therein was found. These mean values were assigned to an imaginary central station whose coordinates were taken as point of departure. Lack of uniformity in the distribution of stations was compensated for by weighting the results. A linear approximation of the form (1) was used, E_0 being the value of the element at the central station in each district. The parameters a and b were found from two equations

of condition, one of which was formed by adding equations of the form (1) for all stations north of the central one and dividing by the total number, and the other equation formed similarly from all stations east of the central one. The values of E_0, a and b having been determined, E was calculated for all points defined by whole degrees of longitude and half-degrees of latitude. Where districts overlapped and there were two calculated values, the mean was taken.

Having thus obtained a lattice of points they next found, by linear interpolation, the position of the isopoints. Smooth curves satisfying the isopoints exactly were then drawn, these being termed district-curves; for the country as a whole a succession of joined district-curves resembled, in general, a slightly zigzag line. Finally, by successive trials, empirical formulas were found to represent smooth curves which approximated the district-curves. These final smooth curves were the terrestrial isomagnetics.

The empirical equations thus deduced by Rücker and Thorpe were of the form

$$E = E_0 + l\lambda + p\phi + m\lambda\phi - n \cos p(\phi - q)$$

where, on the right, only λ and ϕ are the variables, the rest being parameters. Inspection of the results indicates that they could have been fitted more easily by a second-degree parabola of the form (1). Indeed, such a simplification was effected, according to Chree [32], by Mathias and Baillaud [33] who used the data from the nine central stations.

United States charts

A review (apparently the first of its kind) of methods of chart construction employed at the United States Coast and Geodetic Survey up to 1930 is given by W. N. McFarland [13], who made a distinction between analytic and graphical methods.

Isogonic charts of the United States were constructed by the analytic method for the epochs 1850, 1860, and 1870, and for Alaska for the epochs 1885-90, 1895, 1900, and 1902. The magnetic charts of Pennsylvania for the epoch 1842 (based on observations of A. D. Bache), and the D-chart of the Pacific Coast of the United States for 1783 were similarly constructed. This method has not been used by the United States Coast and Geodetic Survey since the edition for epoch 1902 of the D-charts for Alaska, although it was later tried as an aid in construction of a Z-chart for the southeastern United States for epoch 1925.

In constructing a D-chart for Alaska for epoch 1895, Schott [10] used an extension of the Lloyd-Smith method, including all third-degree terms. To reduce the amount of computation the 131 stations were combined into 39 groups, each of which was a mean of from one to 15 observations; these means were given equal weight. From the 39 observation-equations ten normal equations were formed, and solved. In place of the analytic method, mainly from about 1875 to 1930, the graphic method was used "which, briefly stated, consists in drawing the isomagnetic lines free-hand by estimation of their best position without the assistance of any mathematical processes" [13].

There are certain criteria mentioned, however, by McFarland to guide the draftsman in his free-hand tracing: (1) $\Sigma r = 0$; r = residual (chart minus observed value); (2) isolated anomalies of 1° in I or D and

1000 γ in intensity are neglected when they stand alone or are not so supported by neighboring observations to be considered part of a regional disturbance.

Hazard [11] postulated that "the aim should be to draw the lines in such a way that the average difference between plotted values and corresponding values obtained by interpolation between the lines will be a minimum, at the same time that the algebraic sum of the differences is zero."

The device of using group-means instead of individual observed values to reduce the effect of station-anomalies was also employed; one plan of construction of the means was the replacement of each observed value by the mean of itself and observations at adjacent stations.

Hazard [11] notes the use (for the charts of 1925) of a special base-map with proper geographic position of each station indicated by its initial letter; this was said to facilitate considerably the plotting of values. After plotting, free-hand lines were drawn, subject to the criteria noted.

In the case of the Z-chart for that year (1925) plotted values were so irregular that group-means were used. For the southeastern part of the country a cubic approximation derived by least squares was used. The computed values of Z were used as a basis for drawing preliminary curves, which were then modified to fit the observed values more closely.

A discussion of the procedure followed in constructing the D-chart of 1940 for the United States is given by Knapp [14]. This procedure conforms closely to a scheme outlined for production of future D-charts, but has been modified so as not to depart too radically from the method observed in construction of the chart of 1935. Perhaps the main feature of the proposed procedure is the construction of (a) a chart of the "normal field," that is, observed field minus "anomaly-field," and (b) a chart of the anomaly-field. Since the anomalies are, on the whole, relatively constant, the final chart is to be constructed (at 5-year intervals) by superposing the isanomalics on the smoothed normal or "datum"-chart, as it is termed; the datum-chart is to be revised each time in accordance with the pattern of secular change.

Other countries

This descriptive review of methods employed for the construction of magnetic charts in outstanding American and British surveys includes, essentially, the procedures used in magnetic surveys in other countries. Generally, where the surveyed area is relatively small the normal lines are fitted by a linear approximation; where the area surveyed is somewhat larger, a quadratic or cubic approximation is used; where the area is very large the smoothing may be done free-hand or by districting the area and deriving analytic expressions for each district, sketching in the derived curves, and then smoothing and joining at the district-boundaries. There is no uniform procedure used universally, however, and a brief account of methods used in surveys of other countries may be of interest.

To construct isogonics for South Africa for epoch 1936, A. D. Lewis [36] averaged all accepted readings for each geographic degree-square and plotted the mean value in the mean geographic position. Smoothed isogonics were then drawn proportionately between the plotted means.

Whenever an accepted reading differed by more than 1° from the value as interpolated by these smooth isogonics the actual value was given on the map in red.

Tanakadate [37] and Nakano [28] in surveys of Japan derived normal isolines by assuming quadratic approximations. The former survey is noteworthy for the fact that Tanakadate not only reduced his values to a common epoch, but also reduced these values to a common altitude (sea-level). Nakano, whose charts were for the epoch 1913.0, divided the area into two parts, east and west of the meridian 130° east and derived expressions for each area. The isogonics drawn from the two expressions were found to have practically common tangents at the dividing meridian in the northern districts but not in the southern. In the latter region curves running east and west which did not meet were joined on the meridian. For the H-contour a cubic approximation was used.

H. Hatakeyama [26], in a magnetic survey of Formosa for epoch 1936.0, with 26 stations relatively free from unusually large local disturbances, employed a quadratic approximation.

Ljungdahl [4] used a linear approximation for a magnetic survey of Sweden, 1928-30, computations being made on the basis of 53 relatively undisturbed stations. In his report Ljungdahl notes, as did Rücker and Thorpe [34], that the use of least squares requires the deviations to follow the "normal" law, and that this does not apply in the case of magnetic anomalies.

Proposed methods of representation

The lack of uniformity in methods of magnetic cartography, and the frequent failure to include any account of the mapping procedure has, from time to time, drawn comment by magnetic surveyors. Rücker and Thorpe are quoted above. More recently, the question of uniformity of procedure and proposals for new modes of presentation have been discussed by Hellmann [17], Ljungdahl [1, 2, 3], Weinberg [5, 8], and Keränen and others [38, 39].

Hellmann [17, p. 28] summarized his views on magnetic cartography in a number of "postulates." These may be summarized as follows:

(1) The most important task in magnetic cartography is to properly represent the true isomagnetic lines.

(2) A dense network survey is urgently required; isolated measurements are of value.

(3) Charts showing spatial distribution of stations should accompany magnetic maps. The map-scale should not be omitted.

(4) For a precise reduction of magnetic elements measured in the field a portable observatory should be operated if a suitably situated stationary observatory is not at hand.

(5) Values should be determined at regular intervals and at a large number of repeat-stations to enable the drawing of a curve of equal mean secular variation with sufficient accuracy.

(6) Through the diagram or plan of construction it should be made clear to what extent the course of isolines is warranted by the observations. Extension of isolines to very high latitudes might be omitted.

Keränen, Ljungdahl, and Rose [38] recommended:

(1) A central depository be established for results of all magnetic surveys.
(2) A net of repeat-stations be organized all over the Earth to make determinations at common, equidistant epochs.
(3) That the distribution of magnetic elements in separate regions be represented by smoothed isolines with conventional symbolic indication of the departures of observed values from derived values.
(4) That magnetic charts of separate countries should be made so as to render it possible to obtain charts of wider regions by means of simple juxtaposition of charts of adjacent countries.

Ljungdahl notes some of the difficulties in the construction of charts; for example, the definition of "normal" lines, the representation of extreme values when these are relatively isolated, and the assumptions which must be made regarding the behavior of an element in the neighborhood of a station for which there is an observed value. A D-chart for the Baltic Sea for epoch 1938, is presented. The unusual feature of the chart is the absence of true isolines. Symbols in the form of circles varying in size and intensity (open and fully blacked) are used instead. These are placed with reference to normal lines, the size of each circle increasing with increasing departure from normal values.

A similar isogonic chart for the Gulf of Bothnia for epoch 1940, is given [1] by the same author, with directions for its use. In the official publication of this chart (by the Swedish Hydrographic Office) the symbols appear in two colors, red and black, red denoting departure to the west, and black to the east of the normal interpolated values.

Among contemporary investigators, B. Weinberg has contributed a large part of the relatively scant literature on the subject. He has given a detailed account of the procedure used in determining the distribution of H, D, and I in Siberia for epoch 1910 [6]. Weinberg proposes [8] to show, instead of isomagnetics and isopors, two systems of isomagnetics relating (1) to the epoch to which all observations have been reduced, and (2) to some future epoch. An isogonic chart for Finland is shown as an example of this type. In the same article a series of small maps of a selected area is presented to illustrate how the sinuosities of smoothed isolines increase with increasing number of stations.

In discussing some of the assumptions usually made in process of drawing contours Weinberg [5] criticizes the assumptions (1) that an element in the vicinity of the station varies linearly with the distance from the station (this assumption is made in the step of finding the position of the isopoints), and (2) that if the element has the same value at two adjacent stations, then it has the same value (at intermediate points) on the straight line connecting these stations (this assumption is made in the step of drawing the isolines).

It may be said in reply, however, that use of a linear approximation is good enough for most charts. In fact, the error in the charts often does not warrant quadratic interpolation. As noted above, in the actual construction of charts isopoints are usually found by interpolating linearly. Estimates of the value of a point between adjacent isopoints

depend upon the proximity to each other of the latter and how rapidly the function is changing in their neighborhood. Often a plane serves sufficiently well as an approximation to the actual surface. A higher approximation may be warranted when it is known that the function is changing relatively rapidly in the neighborhood of the isopoints.

The geometry of magnetic charts

Published discussions in English of the geometry of isomagnetic charts were scanty until the appearance recently of a valuable series of Notes by Chapman [30] in this JOURNAL. These Notes include discussion of singular points (nodes, cusps, and foci) and of their associated curves. The usefulness is pointed out to the cartographer of the topological theorem that the number of nodes on a simple closed surface is two less than the number of foci, provided the nodes are ordinary. In Note III the isogonic and X- and Y-charts for the field of a centered magnetic dipole are discussed. Since this field is a fair approximation to the Earth's field the properties of the former provide some guidance in construction of the latter. In addition to the four essential singularities at the geographic and magnetic poles, the simple field shows two rectangular nodes; these occur at the intersection of the geographic and magnetic equators.

In this Note it is shown, also, that the fraction of the area of the unit-sphere for which $|D|$ exceeds the obliquity, w, of the magnetic axis (of a centered dipole) is equal to $\{1-[w+2\,(\cot w)\log_n(1+\sin w)]/\pi\}$; this fraction has a finite lower limit, namely $(1-2/\pi)$, which is slightly more than 1/3.

Notes IV and V deal with the nature, properties and occurrence of geomagnetic dip-poles and of the behavior of the magnetic field in their neighborhood.

In Note VI a test for the mutual consistency of isomagnetic charts is proposed and applied to the world charts of the British Admiralty for H and D for epoch 1922. The test is based on the assumption that the Earth's magnetic field, near the surface, has a potential and that, consequently, the vertical component of the curl of the magnetic force vanishes. Application of the test at the 126 lattice-points of a 20° network from 60° north to 60° south, showed 26 points at which the curl-value was outstandingly large (outstanding values were defined as those in excess of 20 units, a unit being 8×10^{-2} milliampere/km^2). Chapman concluded that the estimated curl-values must include a large accidental part merely due to the error of estimation.

In Note VII the nature of the isopors for D, H, I, Z, F, and V (the magnetic potential) is examined and it is shown that the singular points on the isomagnetic chart are not, in general, singular points on the corresponding isoporic chart. The world isoporic charts for H and D, for mean epoch 1922.5, drawn by Fisk [44], are compared with the (less accurate) world isoporic charts for the same epoch prepared by the British Admiralty.

In Note VIII the curl-test is used to determine the mutual consistency of the Admiralty's isoporic chart of H and D at six selected points, and of Fisk's charts at three selected points. These points are where both $(\mathrm{d}H/\mathrm{d}t)$ and $(\mathrm{d}D/\mathrm{d}t)$ vanish. The measure of inconsistency is the time-rate of change of the vertical component of the curl. The charts are

found to be seriously inconsistent, as are Ljungdahl's charts for Sweden for epochs 1929.5 and 1936.5.

Although Chapman's test is of use in revealing the existence of mutual inconsistencies in the H- and D- (or X- and Y-) charts, the test, of itself, provides no means of uniquely determining the corrections to be applied. But it does provide valuable guidance both to the cartographer and to those concerned with planning magnetic surveys.

No mention is made in these Notes of the problem of adjusting the chart of vertical intensity to mutual consistency with the charts of one or more of the other elements.

Choice of map-projection

Of importance in connection with the question of drawing contours is the choice of map-projection. For small regions which are approximately plane the shapes of the isolines remain practically constant, but for large enough regions of the Earth's surface these shapes vary with the projection used. Also, the relative spacing between contours depends upon the projection—a fact which needs to be taken into account in comparing the gradients of field.

The projection most frequently used for world magnetic charts is the Mercator, because the principal use of the D-chart is in navigation; the intensity-charts, however, are seldom used by navigators. For completeness the British Admiralty shows the polar regions in two insets, a practice not so far observed by the United States Hydrographic Office. Except for use in navigation there seems to be no general advantage in representing magnetic contours on a Mercator projection, except where properties of the chart which involve angular relations are to be determined.

For some purposes an equal-area projection may be superior. To cite an instance of minor importance, if an attempt were made to adjust a D-chart to conform to Chapman's relation, noted above (suitably modified for a dipole arrangement giving a better approximation to the Earth's field than a simple centered dipole), which sets a lower limit on that portion of the area of the sphere for which $|D|$ exceeds the obliquity of the magnetic axis, it would be more convenient to use an equal-area projection.

Unless some purpose is served by a special projection it would seem unnecessary to use anything more than a simple rectangular grid with equal spacing of both parallels and meridians. Such a projection was used by Bartels [42] in his maps of the eccentric dipole field, except that the ratio of vertical scale to horizontal scale was (roughly) 5 to 4.

Some suggestions for improving presentation

As a result of this survey it is believed that the usefulness of magnetic charts would be improved if they showed clearly the following information, which, at present, is rarely given in full: The full name of element charted as well as its customary symbol; the physical units to which any numerical values on the chart apply; the epoch for which the chart is valid; the name, or brief description, of area covered; the type of map-projection used and the scale of distances; the name and address of issuing agency; important sources of geomagnetic data.

On the chart itself, where feasible, the location of all stations and the values at observatories, at least, should be listed. In the absence of a universally uniform procedure of construction a description of the method of smoothing, or interpolation, should be given either on the chart or its margin, or, preferably, on an accompanying sheet. It would be desirable to have a criterion generally agreed upon for reference in deciding how closely observed values should be satisfied. It seems reasonable to require that the values at locally undisturbed magnetic observatories be satisfied exactly. In any case the listing of values on the chart enables the reader to determine at a glance the approximate degree of smoothing at any point. Finally, a brief general statement of limitations and an estimate of the errors involved are desirable in validating the claim that the chart has been prepared scientifically.

While this survey is mainly descriptive, the author hopes at some future date to discuss, analytically, bivariate interpolation-formulas which are practicable of application to the problem of the construction of magnetic charts. It is a pleasure to acknowledge the helpful criticisms and the kind encouragement given by J. A. Fleming and E. H. Vestine of the Department of Terrestrial Magnetism.

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AMERICAN MAGNETIC CHARACTER-FIGURE, C_A, THREE-HOUR-RANGE INDICES, K, AND MEAN K-INDICES, K_A, FOR APRIL TO JUNE, 1944

By H. F. Johnston

Summaries of American *URSI* broadcasts have appeared regularly in this Journal since the issue for December, 1930.

As set forth in this Journal for June, 1937, "The Department of Terrestrial Magnetism and the United States Coast and Geodetic Survey with the cooperation of the United States Army and the United States Navy communication-services and several amateur radio stations have undertaken to supply the American character-figure based upon the

Table 1—*American magnetic character-figure C_A for Greenwich half- and full-days based on reports from Cheltenham, Honolulu, Huancayo, San Juan, Sitka, Tucson, and Watheroo for April to June, 1944*

Day	April			May			June		
	0^h-12^h	12^h-24^h	0^h-24^h	0^h-12^h	12^h-24^h	0^h-24^h	0^h-12^h	12^h-24^h	0^h-24^h
1	0.0	0.5	0.2	0.9	1.1	1.0	0.1	0.0	0.0
2	1.9	1.2	1.5	1.1	0.6	0.9	0.0	0.0	0.0
3	1.0	0.4	0.7	0.4	0.2	0.3	0.0	0.1	0.0
4	1.0	0.5	0.8	0.1	1.0	0.6	0.0	0.4	0.2
5	0.9	0.8	0.8	0.7	0.7	0.7	0.3	0.4	0.4
6	1.0	0.6	0.8	0.8	0.6	0.7	0.0	0.1	0.0
7	0.6	0.6	0.6	0.7	0.6	0.7	0.0	0.1	0.0
8	0.4	0.6	0.5	0.8	0.0	0.4	0.0	0.0	0.0
9	0.0	0.5	0.2	0.0	0.1	0.0	0.1	0.1	0.1
10	1.0	0.5	0.8	0.0	0.1	0.0	0.0	0.1	0.0
11	0.4	0.6	0.5	0.1	0.1	0.1	0.0	0.2	0.1
12	0.5	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1
14	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	0.4
15	0.0	0.7	0.4	0.4	0.0	0.2	0.9	0.6	0.8
16	1.1	0.6	0.9	0.0	0.0	0.0	0.6	0.4	0.5
17	0.3	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.2
18	0.1	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.2
19	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
20	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.4
21	0.0	0.3	0.1	0.0	0.0	0.0	1.1	0.4	0.8
22	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.6	0.8
23	0.0	0.0	0.0	0.0	0.3	0.1	0.4	0.4	0.4
24	0.9	0.4	0.6	0.6	0.2	0.4	0.1	0.0	0.1
25	0.1	0.1	0.1	0.2	0.2	0.2	0.0	0.3	0.1
26	0.5	0.4	0.4	0.5	0.2	0.4	0.5	0.8	0.6
27	0.5	0.4	0.5	0.5	0.2	0.4	0.6	0.1	0.4
28	0.6	0.4	0.5	0.2	0.3	0.2	0.0	0.1	0.0
29	0.6	0.4	0.5	0.8	0.9	0.9	0.6	0.0	0.3
30	0.9	0.5	0.7	0.6	0.4	0.5	0.4	0.1	0.2
31				0.4	0.5	0.4			
Means	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2

Table 2--Three-hour-range indices, K, April to June 1944

April 1944

	1	2	3	4	5	6	7	8
Si	2011 2232	4499 8343	4543 2232	2367 5332	2555 3433	3268 4332	3253 3334	2214 6222
Ch	3001 1134	4577 5344	6532 2223	3344 2333	4543 3334	4454 2333	5343 2345	4212 4232
Tu	3112 2233	5677 5343	5532 2233	3445 2323	3534 2334	3354 2332	5243 2234	3212 5222
SJ	2001 1234	4556 3232	5421 1122	2343 2222	3433 2233	3143 1322	4232 1133	3102 3122
Ho	a)---- ----	---- ----	---- ----	---- ----	---- ----	¨3133 2211	2022 1221	1110 2110
Hu	3111 3333	4555 4452	3421 2242	2232 4322	3321 3432	3132 3422	2112 2343	2111 4322
Wa	1122 2233	3477 6443	4432 2222	1346 4322	2334 3453	2245 4432	4332 2234	2223 5222

	9	10	11	12	13	14	15	16
Si	1220 1223	3565 4212	3131 2332	3232 2010	0010 0000	0000 1000	1002 2133	4377 6632
Ch	1220 0234	3555 2223	4132 1233	5221 1121	0110 0001	1001 1000	2001 2245	5554 4323
Tu	1221 1244	2654 2323	4132 2333	5331 1011	1110 0011	0001 1111	2002 3245	5455 4322
SJ	0110 1233	2433 2212	4122 0322	4111 0010	0000 0000	0001 0110	0000 4244	4343 3312
Ho	0111 1211	1332 2211	1111 1111	1111 0100	1110 0001	1101 1100	1101 2112	2113 3210
Hu	1110 2332	2422 2322	3122 2433	4121 2220	0000 1100	0012 2210	0001 3333	3224 3322
Wa	1211 1234	1344 4322	2112 2423	2222 1121	0100 0110	0112 1100	0001 3233	4234 6532

	17	18	19	20	21	22	23	24
Si	3213 2211	2021 0111	2012 1200	1122 2100	0113 4110	1011 1000	0000 1000	3353 2211
Ch	4212 1123	4121 0002	2000 0011	2312 1011	0121 2111	0001 0002	0010 1110	3433 3233
Tu	4313 1113	3021 0012	2001 1110	1112 1121	1121 3211	1010 0001	0010 0000	3544 3223
SJ	3301 0102	4010 0001	2000 0010	1202 0100	0011 2210	0000 0001	0010 1010	3433 2122
Ho	1111 1201	1010 0111	1001 0111	1111 0110	0111 1111	1000 0101	0010 1100	2121 1111
Hu	3201 1232	3010 2221	1000 1211	1101 1210	0111 3321	0000 0101	0000 2110	3232 4322
Wa	2112 2221	2111 1111	1011 2211	1111 0120	1112 3211	1010 0101	0011 1110	3433 2121

	25	26	27	28	29	30
Si	2221 1121	2332 1221	2434 3322	2442 2321	1352 3211	2576 2313
Ch	3320 1123	2331 1232	3332 1133	4442 2232	1343 3233	2455 2224
Tu	4220 1133	2331 2243	2433 1223	3442 2222	2443 3222	2465 2325
SJ	3300 1111	2321 1332	2322 0222	3322 1222	1232 3211	2444 C213
Ho	1111 1111	1111 1111	1211 1111	1221 1211	1121 2211	1354 1213
Hu	3211 2221	2321 2321	2322 2222	3322 3321	1332 4321	2322 2322
Wa	2211 2232	1321 1331	1223 3421	2222 2341	1233 4221	1453 2222

May 1944

	1	2	3	4	5	6	7	8
Si	3246 7634	3546 6321	2233 4311	2114 4344	4235 5332	3246 4332	2354 4323	3443 2112
Ch	3343 4445	4434 4323	4321 2221	1113 3344	4223 4342	5333 3343	3342 3332	4443 1112
Tu	4433 5535	3534 5232	3232 2211	1113 3455	4334 3333	4334 3333	3343 2323	4443 1112
SJ	3342 4444	3433 4212	3211 2110	1012 2244	3112 3222	3222 3222	2242 1221	4311 0100
Ho	3223 4333	1323 3111	1112 2111	1112 2333	2213 2111	1123 1211	1232 1111	2232 1111
Hu	3332 3443	2433 3422	2211 3210	1002 2444	3212 3331	3222 4322	2232 3421	3311 1210
Wa	1335 6543	2445 4321	1112 4211	1114 4354	3223 4232	3225 4342	1243 3344	2332 1111

	9	10	11	12	13	14	15	16
Si	0221 1121	2011 1111	1121 1222	2012 1111	1011 1010	1121 1111	2340 1111	0110 1111
Ch	0121 1132	3201 1122	1321 1223	2112 1122	0111 0112	1221 0011	3331 0011	0110 1011
Tu	1111 1121	2100 1122	2221 1112	3122 1123	1111 0002	1321 1112	3440 1211	0111 1112
SJ	0110 0110	3000 0001	0210 0111	0012 0112	0110 0001	0110 0001	2331 0000	0000 1100
Ho	1111 1110	1100 0111	0100 1111	1111 1101	0010 1110	1111 0001	2220 0000	0011 1111
Hu	0110 2121	2000 1112	1211 2221	2001 2222	0011 2211	1111 1111	2320 1100	0001 2110
Wa	1011 0031	1010 0011	1111 1111	1111 0121	1100 1001	1111 0111	2121 1211	0110 1111

	17	18	19	20	21	22	23	24
Si	1211 1012	1101 1022	1121 1111	1000 0000	1102 0111	0121 1221	2223 2122	2353 1122
Ch	2101 1012	1011 0002	1111 1113	1001 0111	2011 0012	1021 1222	2311 1223	3232 2233
Tu	2111 1112	0101 1122	1110 1122	1000 1121	2101 0012	2122 2222	2322 2222	4342 2223
SJ	0000 0011	0000 0101	1001 1101	0000 0000	1000 0000	0011 0111	1101 1112	3231 1121
Ho	1101 0111	0101 0011	0011 1111	0100 0111	1111 0011	1111 1111	0111 1111	2221 1111
Hu	0101 2110	0000 1111	1110 2211	0000 1110	1000 0110	1012 2210	1101 3222	3231 2211
Wa	1111 1011	1211 0111	1111 1211	0000 0110	1111 0211	0101 1111	1212 3222	2233 1132

	25	26	27	28	29	30	31
Si	2332 3222	3223 1121	2333 3122	2221 1213	3434 3334	4344 4312	2341 1323
Ch	1321 2133	3322 2232	3333 2212	2132 2223	4345 3346	3342 2223	1332 2324
Tu	1331 1132	4332 2122	2432 3222	2132 2223	4334 3335	3333 3222	2332 2423
SJ	1311 0022	2221 1111	1422 1111	1022 2211	3234 2324	3232 2211	1320 1322
Ho	1121 2121	3321 1121	2323 2111	1122 1102	3233 2213	1233 2111	1322 1222
Hu	1310 1231	3221 3321	1322 2220	1122 2212	3222 3434	2222 3211	1222 2431
Wa	1121 3231	2222 1111	1323 2221	1122 2212	4223 3433	3234 3211	1322 2433

¨Interpolated. a)Honolulu not reporting April 1-5.

Table 2--Three-hour-range indices, K, April to June 1944--concluded

June 1944

	1	2	3	4	5	6	7	8
Si	2122 1221	1113 2122	1131 1111	1111 1123	2122 2222	2211 1121	0122 1111	1101 1111
Ch	3121 1221	1122 1122	1121 0033	2111 1144	3222 2232	1210 0222	1021 1112	0110 0121
Tu	3232 1222	1122 1121	2221 1022	2122 2245	3232 2233	2221 1221	1121 2213	0111 1122
SJ	2121 1210	1112 1010	0010 0122	1111 1133	2222 1221	1110 1110	0020 2211	0101 2010
Ho	1122 0100	0112 1111	1110 0111	1122 1133	3221 1211	1110 1111	1011 0111	0100 1110
Hu	1111 2320	0111 2121	0011 1011	1011 2233	2122 2431	1111 2330	0010 2321	0101 2220
Wa	2121 1221	1112 2122	1111 1010	1122 1132	1221 2221	1111 1111	0111 1111	0111 1211
	9	10	11	12	13	14	15	16
Si	2212 2122	2111 1112	1111 1232	1121 1110	1111 2232	2222 2114	4352 3223	3244 4222
Ch	1221 2223	3111 1122	2111 1222	2211 0210	0111 2222	3112 2125	4442 2334	4232 2233
Tu	2221 2223	2011 1111	2121 1323	2211 1111	0212 2122	3222 3115	4351 2224	4233 3223
SJ	1221 2211	3000 1211	1111 0210	2110 0100	0110 2122	2102 3123	4431 1222	3122 1122
Ho	2221 2111	1010 1010	1111 1210	1001 1010	1101 2122	2101 3113	3332 1222	1113 3021
Hu	1220 3221	2100 2221	1011 2321	2210 1210	0111 2222	2102 4223	3332 3322	3221 3321
Wa	1221 2311	1111 1111	1111 2321	1111 1211	0111 2222	1112 3113	3332 3433	1324 3222
	17	18	19	20	21	22	23	24
Si	2230 2212	2332 2211	2313 2112	2443 1123	3454 2221	3456 2332	2253 2322	2231 2211
Ch	2331 1223	2322 1222	2312 0113	3332 1134	4455 2233	3534 2434	2152 2334	3321 1012
Tu	3331 2313	3332 1122	3322 1213	3333 1223	4555 2333	4444 3433	2253 2433	2221 1112
SJ	1220 1112	1313 1111	1112 0012	2223 1113	3434 1223	3424 1312	1242 1212	2211 2111
Ho	1121 1112	1231 1111	1222 0002	1222 0103	3443 2112	2432 1321	1142 1211	1111 1100
Hu	1221 2312	1311 2211	1111 2211	2231 2223	3432 2332	3321 3532	1131 2421	2211 2221
Wa	2221 2323	2322 2221	1222 2213	1232 2223	2333 3222	2433 2523	2243 2323	2222 2211
	25	26	27	28	29	30		
Si	1210 1221	2333 4432	2234 3222	1222 1112	3433 2211	2224 4211		
Ch	2210 0332	2333 3334	4433 1323	1222 2223	2421 1221	3232 2213		
Tu	2221 1232	3332 2353	4433 2223	2322 1214	3532 2321	2233 2213		
SJ	0210 0221	1332 2233	3311 0212	1222 1122	2411 1200	2232 2001		
Ho	1221 1222	2121 2332	1223 0111	1211 1112	2322 1101	1232 2011		
Hu	1111 2331	2322 4443	3212 2321	1212 3221	2321 2311	1222 2200		
Wa	1121 1121	2132 5443	2223 2223	1212 1111	2422 2211	2133 3212		

Table 3--Weighted average of reduced three-hour-range indices, April to June 1944

Day	April 1944[a]									May 1944									June 1944								
	Values K_A								Sum	Values K_A								Sum	Values K_A								Sum
1	2^x	0^x	1	1^x	2	2	3	3^x	16	2^x	2^x	3	3^x	5	4^x	3^x	4	28^x	2	1	2	1^x	1	2	1^x	1	12
2	4	4^x	7	7^x	5^x	3^x	4	3	39	2^x	4	3	4	4	2^x	2	1^x	23^x	1	1	1^x	2	1^x	1	2	1^x	11^x
3	4^x	4^x	3	2	2	2	2^x	2^x	23	2^x	1^x	1^x	2	2^x	2	1	1	14	1	1	1^x	1	0^x	0^x	1^x	1	8
4	2	3	4	4^x	3	3	2	2^x	24	1^x	1	1	3	3	3	4^x	4	21	1^x	1	1^x	1^x	1	1	3.	3	13^x
5	3	4	3^x	3^x	3	3^x	3	3^x	27	3^x	2	2	3	3^x	2^x	3	2	21^x	2	1^x	2	2	1^x	2	2^x	1^x	15
6	3	2^x	4	4^x	2^x	3^x	2^x	2	24^x	3^x	2	2^x	3^x	3^x	3	3	2	23	1^x	1^x	1	1	1	1^x	1^x	1	10
7	4	2	3	2^x	2	2^x	3	4	23	2	2^x	4	2^x	2^x	2^x	2^x	2^x	21	0^x	0^x	1^x	1	1	1^x	1	1^x	8^x
8	2^x	2	1	2	4	2	2	2	17^x	3	3	3	2^x	1	1	1	1	15^x	0	1	0^x	1	1	1	1^x	1	7
9	1	2	1^x	0^x	1	2^x	2^x	3^x	14^x	0^x	1	1^x	1	1	1	2	1	9	1^x	2	2	1	2	2	1^x	1^x	13^x
10	2	4	4	3^x	2^x	2^x	1^x	2^x	22^x	2	0^x	0^x	0^x	0^x	0^x	1	1^x	7	2	0^x	1	1	1	1	1	1	8^x
11	3	1	2^x	2	1^x	3	2^x	2^x	18	1	1^x	1^x	1	1	1^x	1^x	1^x	10^x	1^x	1	1	1	1	2^x	2	1^x	11^x
12	3^x	2	2	1^x	1	1	1	0^x	12^x	1^x	0^x	1	2	1	1	1^x	1^x	10	1^x	1	1	1	0^x	1^x	1	0^x	8
13	0^x	0^x	0^x	0	0	0	0^x	0^x	2^x	0^x	0^x	1	0^x	0^x	0^x	0^x	1	5	0^x	1	1	1	2	1^x	2^x	2	11^x
14	0^x	0^x	0^x	1^x	1	0^x	0	0	4^x	1	1^x	1^x	1	0^x	0^x	0^x	1	7^x	2	1	1	2	2^x	1	1^x	3^x	14^x
15	1	0	0	1^x	3	2	3	4	14^x	2^x	2^x	2^x	0^x	0^x	1	0^x	0^x	10^x	3^x	3	3^x	2	2	3	2^x	3	22^x
16	4	3	4	4^x	4	4	2	2	27^x	0^x	0^x	1	0^x	1	1	1	1	6^x	2^x	2	2^x	3	2^x	1^x	2	2	18
17	3	2	1	2	1^x	1^x	1	2	14	1	1	0^x	1	1	0^x	1	1^x	7^x	2	2	2^x	1	1^x	2	1^x	2^x	15
18	3	0^x	1^x	1	0^x	1	0^x	1^x	9^x	0^x	1	0^x	1	0^x	0^x	1	1^x	6^x	2	2^x	2	2	1^x	1^x	1^x	1	14
19	1^x	0	0^x	0^x	1	1	0^x	0^x	5^x	1	1	1	1	1	1^x	1	1^x	9	1^x	2	1^x	2	1	1	1	2^x	12^x
20	1^x	1^x	1	1^x	1	1	0^x	0^x	8^x	0^x	0	0	0	0	0^x	1	0^x	2^x	2	2^x	2^x	2^x	1	1^x	2	3	17
21	0^x	1	1^x	1^x	2^x	2	1	0^x	10^x	1^x	0^x	0^x	1	0	0^x	1	1	6	3	3^x	4	3^x	2	2	2^x	2	22^x
22	1	0	0^x	0^x	0	0^x	0	1	3^x	0^x	0^x	1^x	1^x	1	1^x	1^x	1	9	3	3^x	3	3^x	2	4	2^x	2^x	24
23	0	0	1	0	1	0^x	0^x	0	3	1^x	2	1	2	2	1^x	2	2	14	1^x	1^x	4	2^x	1^x	3	2	2^x	18^x
24	3	3^x	3	2^x	2^x	2	1^x	2	20	2^x	2	3	2	1^x	1^x	2	2	16^x	2	2	2	1^x	1^x	1^x	1	1	12^x
25	2^x	2^x	1^x	0^x	1^x	1^x	2	2	14	1^x	2	2	1	2	1^x	2^x	1^x	14	1^x	1^x	1^x	0^x	0^x	2	2^x	1^x	11^x
26	2	3	2^x	1^x	1^x	2^x	2^x	1^x	17	3	2	2	2	1^x	1^x	2	1	15	2	2	3	2^x	3^x	3^x	3^x	3	23
27	2	3	2^x	2^x	2	2^x	2	2	18^x	2	3	2^x	2^x	2	1^x	1^x	1^x	16^x	2^x	2^x	2	3	1^x	2	2	2^x	18
28	2^x	3	3	2	2	2^x	2^x	1^x	19	1^x	1	2	2	2	2	1	2^x	14	1^x	2	1^x	2	1	1^x	1	2	12^x
29	1^x	2^x	3^x	2^x	3	2^x	1^x	1^x	18^x	3^x	2^x	3	3^x	2^x	3^x	3	4	25^x	2^x	3^x	2	2	1^x	2	1	1	15^x
30	2	4	5	4	2	2^x	1^x	3	24	3	2^x	3	3	2^x	2	1^x	1^x	19	2	1^x	3	2^x	2^x	1^x	1	2	16
31										1^x	2^x	2^x	2	1^x	3^x	2^x	2^x	18^x									

[a] Honolulu not reporting April 1-5.

reports of the seven American-operated observatories—those of the Department of Terrestrial Magnetism at Huancayo in Peru and at Watheroo in Western Australia, and those of the United States Coast and Geodetic Survey at Cheltenham (Maryland), Honolulu (Hawaii), San Juan (Puerto Rico), Sitka (Alaska), and Tucson (Arizona." This character-figure is being designated C_A, and its values for the first twelve, the second twelve, and all twenty-four hours of each Greenwich day for April to June, 1944, are given in Table 1.

The three-hour-range indices, K, have been compiled since April 6, 1940, for each of the seven American-operated observatories. The eight indices for each day give geomagnetic activity for three-hour periods successively during the Greenwich day. The indices range from "zero" very quiet to "nine" extremely disturbed. The K-indices for Sitka (Si), Cheltenham (Ch), Tucson (Tu), San Juan (SJ), Honolulu (Ho), Huancayo (Hu), and Watheroo (Wa), for April to June, 1944, are given in Table 2. Interpolated indices are shown thus, $\ddot{3}$.

In the manner set forth in the Journal for September, 1940, the indices are standardized into reduced indices K_r to eliminate local variations. A weighted mean index K_A, is derived from the reduced indices. The reduced indices from Si, Ch, and Wa are given double weight and those from Tu, SJ, Ho, and Hu are given single weight. The weighted indices, K_A, for April to June, 1944, are given in Table 3. A superior cross ($^\times$) following an index-number denotes a half-unit, thus $5^\times = 5.5$, etc.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington 15, D. C., July 28, 1944

SOME EARLY CONTRIBUTIONS TO THE HISTORY OF GEOMAGNETISM—VII

By H. D. Harradon

João de Castro was a Portuguese naval commander and explorer, born in Lisbon in 1500, the son of Alvaro de Castro, governor of that city. As a young man he distinguished himself in the campaigns against the Moors in North Africa. In 1545 he was sent to the "Indies" with six ships where he overthrew Mahmud, King of Gujarat, relieved the besieged town of Diu, and achieved a number of other military successes.[1] In 1547 he was appointed Viceroy of India by João III, but soon after receiving his full commission he died at Ormuz, June 6, 1548.[2] His ashes were later brought to Portugal and repose today in the Dominican Convent at Bemfica, near Lisbon. Among the illustrious captains sent out to India by Portugal, only Vasco da Gama and João de Castro are said to have been honored by statues erected to their memory. The statue of the latter is over the principal entrance to Goa.

In order to test the two methods first tried by Pedro Nunes at Evora in 1533, the Infante Dom Luiz, who had himself received mathematical and astronomical instruction from Pedro Nunes and was greatly interested in all nautical questions, turned over an instrument[3] to his fellow student and friend João de Castro, who was in command of one of the 11 ships that sailed in 1538 to India, and enjoined him to test and investigate carefully the instrument as well as the new method of latitude-determination, a commission which he executed most brilliantly. He not only determined the magnetic declination as often as possible but also made all kinds of observations of the method itself, of the effects of the magnetic needles and their magnetization on the observed declination-values, of magnetic storms, of the deviation of the compass, etc. He even discovered the magnetization of rocks regarding which we find no mention in other European literatures before the 17th century. De Castro also continued his observations on the voyage along the west coast of India and into the Red Sea so that we possess for the years 1538-41 a series of 43 declination-values, the first series of its kind that has come down to us. De Castro kept very extensive journals regarding all his nautical, magnetic, meteorological, and hydrographical observations and these certainly contain the largest and most valuable collection of such observations from the first half of the 16th century and deserve the zealous study of all who intend to write the history of the physical geography or navigation of that period. Hellmann considered João de Castro as the most

[1]As an indication of the high esteem in which de Castro was held by the Portuguese, attention may be called to the great national epic "Os Lusiadas" of Luiz de Camões, in which de Castro is mentioned a number of times, as for example in the following (Canto 1ª, est. 14ª):

> Nem deixarão meus versos esquecidos
> Aquelles que nos reinos lá da Aurora
> Se fizerão por armas tão subidos . . .
> Albuquerque terribil, Castro forte,
> E outros em quem poder não teve a morte.

[Never shall my verses leave forgotten those who, with high martial valor, established our dominions in the East—terrible Albuquerque and brave Castro and others over whom death had no power.]

[2]According to the inscription on the monument erected to de Castro's memory by his grandson—"Obiit octavo Id. Jun. anno M.D.XLVIII. Aetatis XLVIII."

[3]Terr. Mag., **48**, 197-199 (1943).

outstanding representative of scientific oceanography during the closing years of the age of discovery.

The log-books or "Roteiros" kept by João de Castro on his voyages during the years 1538-41 which he transmitted to his sovereign, the Infante Dom Luiz, remained for three centuries in the archives of Portugal practically unused until they were brought to light and published by Nunes de Carvalho, Diogo Köpke, and João de Andrade Corvo. These publications are as follows:

(1) Roteiro de Lisboa a Goa por D. João de Castro. Annotated by João de Andrade Corvo. Lisboa 1882. 8°, with maps and illustrations.

(2) Primeiro Roteiro da Costa da India desde Goa até Dio: Narrando a viagem que fez o Vice-Rei D. Garcia de Noronha em socorro deste ultima cidade. 1538-1539. Por Dom João de Castro, Governador e Vice-rei, que depois foi, da India, Segundo MS. Autographo. Published by Diogo Köpke. Porto 1843. 8° with portraits and illustrations, as well as an atlas of charts and plans.

(3) Roteiro em que se contem a viagem que fizeram os Portuguezes no anno de 1541, partindo da nobre cidade de Goa atee Soez, que he no fim, e stremidade do Mar Roxo. Com o sitio, e pintura de todo o syno arabico por Dom Ioam de Castro, decimo terceiro governador, e quarto viso-rey da India . . . pelo Doutor Antonio Nunes de Carvalho . . . Paris 1833. 8°, with portraits and one map, as well as an atlas of maps and plans.

These journals contain a detailed record of de Castro's magnetic measurements of which selections are given below. As a rule, several determinations of azimuth were made both before and after noon; those corresponding to equal solar altitudes were combined and thus many values of the deviation of the magnetic needle were obtained. These agreed very well with one another since the differences vary between only 0° and 3/4°. These differences may not be regarded wholly as errors of measurement, since, indeed, apart from other inaccuracies, those real differences in declination resulting from the forward movement of the ship could not be taken into account.

The above information is derived largely from Hellmann's introduction to No. 10 of his "Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus."

We are indebted to Dr. J. de Sampaio Ferraz, of Rio de Janeiro, for the following translations. Dr. Sampaio Ferraz had the advantage of consulting especially the rare books of the Naval Library of Brazil. His friend Commander Radler de Aquino, well known for his navigation tables, was kind enough to read the translations. Dr. Sampaio Ferraz makes the following comment: "The author (in the copies at Evora Library on which the text is based) is confusing in the naming of the rose's sectors NW and NE, written in different ways. I adopted the following basis: 'Noroestear' and 'norestear' are the two forms employed in the text to designate northwesting and 'nordestear' is the only form used to name northeasting. But only a check of the individual sets of observations will show if our basis has failed. As I point out in one of my notes, the most authoritative commentator of de Castro's log-books, Commander Fontoura, has apparently been a victim himself of the variable forms for designation of sectors. Commander Radler de Aquino agrees with my note on Fontoura's seeming error."

EXTRACTS ON MAGNETIC OBSERVATIONS FROM LOG-BOOKS OF JOÃO DE CASTRO, 1538-1539 AND 1541

Translated by J. de Sampaio Ferraz

Lisbon to Goa, 1538

At dawn, on Saturday, April 13, we saw Palma, which is one of the Canary Islands, hastening to set up the dial-plate and shadow-instrument **[1]**[a], a gift from the very excellent Prince, the Infante Dom Luiz, moved by the intense desire to ascertain two things: First, if on this island the needles varied or not [**2**], for many pilots usually found that in this place and meridian the needles sought the true pole of the Earth [**3**]; second, if the rule established by Doctor Pedro Nunes was true and accurate, that at every hour of the day in which shadows are obtainable, the altitude of the pole can be determined [**4**]. With which instrument were made the following observations, with no wind, so that the ship could not be steered all day.

First observation before noon

The Sun being in altitude 57°, the style cast its shadow at 71°, reckoning from north to west.

Second observation before noon

The Sun being in altitude 61°, the style cast its shadow at 64°, reckoning from north to west.

Having thus determined at every hour the Sun's altitude, I waited till after midday, when the Sun would be at the two altitudes observed in the morning, in order to ascertain how the needles behaved in the meridian of these islands, obtaining the following results.

First observation after noon

The Sun being in altitude 61-1/2°, the style cast its shadow at 53°, reckoning from north to east.

Thus, in this set of observations, the arc before midday is longer than the afternoon arc by 11°, which halved gives 5-1/2°, the amount the needle swings to northeast in this place.

Second observation after noon

The Sun being in altitude 57°, the style cast its shadow at 60°, reckoning from north to east.

Thus, in this set of observations, the arc after noon is 11°, which halved gives 5-1/2°, the amount the needle deviates to northeast in this place.

All throughout Monday, April 15, the wind blew fresh from west-northwest; we steered south by west. On this day I made the following observations.

First observation before noon

The Sun being in altitude 56°, the style cast its shadow at 80°, reckoning from north to west.

[a]The notes indicated by bold-face type are given at the end of the translation of excerpts from each log-book.

Second observation before noon

The Sun being in altitude 67°, the style cast its shadow at 65°, reckoning from north to west.

First observation after noon

The Sun being in altitude 67°, the style cast its shadow at 53°, reckoning from north to east.

Thus, in this set of observations the arc before noon is greater than the afternoon arc by 12°, whose half, 6°, is the amount the needle deviates to northeast in this place.

Second observation after noon

The Sun being in altitude 56°, the style cast its shadow at 68°, reckoning from north to east.

Thus, in this set of observations, the arc before noon is greater than the afternoon arc by 12°, which halved gives 6°, the amplitude of the oscillation to northeast.

Annotation—Despite the similarity and consistency of today's observations, there is no reason to underrate the mystery of the northeasting of the needles, or to make it a fast rule that the needle has varied necessarily 1/2° in the course made from Saturday, April 13, when I took the other observations, to the point where I am today, Monday, the 15th of same month. As the style's shadow is restless along the circumference of the graduated circle, owing to the constant movements of the ship, and also, as the wind is rather stiff, the shadow-instrument gets out of level and becomes less accurate, through derangement of the gimbals, all these troubles rendering it a difficult problem to determine exactly the position of the shadow. So that if the ship rolls strongly, it will lead us easily to an error as large as 2°; but if it sails firmly and smoothly, whoever possesses good estimating power cannot err above 1/2°. And considering that the two above-mentioned sets of observations were made on the meridian of the Canary Islands, the first, north of same, and the second, when I was south of them, finding through both that the needles swayed to northeast from 5-1/2° to 6°, the opinion is therefore false of those who maintain that on the meridian of these islands the needle seeks the true poles of the world [**5**].

This Cape of Agulhas is the place where the pilots take for granted that their needles suffer no deviation, but point straight to the true poles of the world, this being the reason for its name, that is, where the needles do not change. When land was first sighted, I was 120 leagues astern of it, or 110, according to the pilot's estimate.

Very important and useful annotation—To find myself already in these regions so desired by navigators after enduring so many fears and apprehensions, so many intense adventures over so vast and stormy a sea, offers me the opportunity to say something regarding the extension of the way made, a matter certainly as useful as it is relevant and beautiful, and which up to now can be said to have been discussed but not established; and as the enlightment and solution of this doubt demands not only demonstrations of mathematicians, but also the experience and opinions of pilots and mariners, who for many years have plied this ocean, a great and infinite sea, I will expose here the conclusions arrived

at after considering both those aspects and employing the shadow instrument invented by Doctor Pedro Nunes, a famous mathematician of our times, and built by the hands of João Gonçalves, whose ingenuity triumphs in contemporary Europe, and, is above all, approved by the most excellent Prince, the Infante Dom Luiz. Among other favors which I received from His Highness for this journey, was the gift of this instrument with which we obtained the altitude of the pole at every hour of the day, and thereby the real variation of the needles, leading us to ascertain the extension of the lands and the difference of meridians. Consequently it will be fair to rely on an instrument of such authority and on whatever, reputed exact, is derived from it.

Here begins the proof—In Lisbon, as I have often determined, the northeasting of the needles amounts to 7°, and navigating from that city towards Brazil, when we reach the Canary Islands, the needles deviate less by 1-1/2°, reducing here the northeasting to 5-1/2°, which is maintained to the equinoctial line. However, ahead of this line, in the direction of Brazil, the variation starts to increase gradually, so that when we are 130 leagues to the east of Cape Santo Agostinho and at latitude 9°, the northeasting of the needles reaches 10°, and from here onward, the deviation grows greater and greater always in the northeastern sector, until, at 230 leagues astern of Tristão da Cunha Islands, on the parallel of 31-1/2°, where the meridian should run 2° to the east of Cape St. Vincent's meridian, the variation of the needles reaches the extreme value of 19-1/2° or 20°; beyond this meridian, on the way to the Cape of Good Hope, the needles start backing gradually, reducing the degrees already gained, that is, now diminishing the needles' variation. This goes on until we are as far ahead as the first promontory of Natal Land, which lies at latitude 32°, where the needles' north and *fleur de lis* seek the true pole of the world; but advancing from this place towards India, the needles deviate in the opposite direction, turning their north and *fleur de lis* to the northwestern sector, and the further we go, the variation increases, until we reach the coasts of India, where the north of the needles deviates from the pole of the world 11° to northwest, that is a 1/4 [**6**].

On Wednesday, July 3, the wind was from the northeast; we steered to the northwest; again heading towards land we reached it at ten o'clock. On this day I made the following observations.

First observation before noon

The Sun being in altitude 16°, the style's shadow fell on 50°, reckoning from south to west, it being then half past eight.

Second observation before noon

The Sun being in altitude 25°, the style's shadow fell on 39-1/2°, reckoning from south to west, it being then nine forty.

Third observation before noon

The Sun being in altitude 31-1/2°, the style's shadow fell on 25°, reckoning from south to west, it being then half past ten.

First observation after noon

The Sun being in altitude 31-1/2°, the style's shadow fell on 25°, reckoning from south to east, it being then half past one.

Thus, in this set of observations, the afternoon arc was equal to the morning one, from which it is clear that in this place the needles do not vary by any amount.

Second observation after noon

The Sun being in altitude 25°, the style's shadow fell on 39-1/2°, reckoning from south to east, it being then quarter past two.

Thus, in this set of observations, the afternoon arc was equal to the morning one, from which it is clear that in this place the needles have no variation.

Third observation after noon

The Sun being in altitude 16°, the style's shadow fell on 50°, reckoning from south to east, it being then quarter past three.

Thus, in this set of observations, the afternoon arc was equal to the morning one, from which it is clear that in this place the needles do not vary.

At noon on this day we observed the Sun, whose maximum altitude from the horizon was 36°; its declination on this date was 22°, from which it followed that we were at a latitude of 32°, corresponding to the first headland of Natal [7]; from which is manifest that in this meridian which runs through the mentioned point, the needles do not vary by any amount, but seek directly the true poles of the world, as proved by so many and consistent observations.

On this day I wished to work with the shadow-instrument to verify the variation of the needles, and it being earlier than 11 o'clock, the style's shadow fell far beyond the noon-line, so that, sending for several needles to compare them with the instrument, I found them so disturbed as to surprise me greatly, for while one pointed to the east, another pointed to the north. This kept me very irresolute until I found out the cause, that is, a cannon which was close by the spot where I intended making the observations, whose iron attracted the needles and thus deflected them. From this I concluded that the set of observations I made on June 30, in the meridian 5-1/2° east of Cape Agulhas, and which I found very contradictory, as well as other sets obtained near Brazil, with noted differences, was troubled by the proximity of artillery pieces, anchors or other iron. I examined all parts of the ship in search of a convenient place to make observations.

On August 6 I desired to find the variation of the needles in this port of Mozambique, and made the following observations.

First observation before noon

The Sun being in altitude 16°, the style's shadow fell on 76-1/2°, reckoning from south to west.

Second observation before noon

The Sun being in altitude 42-1/2°, the style's shadow fell on 61-1/2°, reckoning from south to west.

Third observation before noon

The Sun being in altitude 53°, the style's shadow fell on 48°, reckoning from south to west.

Fourth observation before noon

The Sun being in altitude 56-2/3°, the style's shadow fell on 39°, reckoning from south to west.

First observation after noon

The Sun being in altitude 56-2/3°, the style's shadow fell on 25-1/2°, reckoning from south to east.

Thus, in this set of observations the arc before noon was greater than the afternoon one by 13-1/2°, which halved gives 6-3/4°, the amount the needle swings to northwest in this place.

Second observation after noon

The Sun being in altitude 53°, the style's shadow fell on 34-1/2°, reckoning from south to east.

Thus, in this set of observations the arc before noon was greater than the afternoon one by 14°, whose half, 7°, represents the amount of northwesting of the needle in this place.

Third observation after noon

The Sun being in altitude 42-1/2°, the style's shadow fell on 48°, reckoning from south to east.

Thus, in this set of observations the arc before noon was greater than the afternoon one by 13-1/2°, the half of which value, 6-3/4°, corresponds to the amount of northwesting of the needle in this place.

Fourth observation after noon

The Sun being in altitude 16°, the style's shadow fell on 63-1/2°, reckoning from south to east.

Thus, in this set of observations the arc before noon was greater than the afternoon one by 13°, half of which, 6-1/2°, is the amount of northwesting of the needle in this place.

Friday, August 9, I again tested the variation of the needles, obtaining in all sets of observations 6-1/2° to 6-3/4° for the values of their northwesting; and all the time we were in this port the wind blew from the east except on two days when we had some wind from the west.

Observations made with the Sun rising and setting to obtain the variation of the needles—On this day, as the Sun rose on the horizon, the style's shadow was cast on the dial-plate right over the east-west line of the graduated circle, that is, 90° from south or north by west; and just before sunset, the style's shadow fell on 74-1/2°, reckoning from south to east.

Thus in these observations the morning arc was greater than the afternoon arc by 15-1/2°, whose half, 7-3/4°, represents the northwesting of the needles in this place.

Notes on the determination of the needles' variation by two methods—From the set of observations of this day, August 24, it follows that this was the occasion on which further proofs were obtained of the northwesting of the needles, considering the determinations were made by two very different methods: One was the usual process employed on this journey, by the amount some arcs are greater than others; and the other, observing only at the rising and setting of the Sun—not a general but

only a particular case, for those who find themselves in a right or almost right sphere, as it happened to me today. This is so, for as I have already stated in connection with the observations made on August 22, for those in a right sphere it will always occur that the horizon's arc between the point where the Sun rises and the equinoctial line, called by mathematicians the amplitude of the sunrise, is equal to the declination of the day in question. And as today's declination is 7° 50′, admitting my needle had no deviation and sought the true poles of the world, the style should have cast its shadow, at sunrise, on 7° 50′, west to south; and yet the shadow fell on the east-west line, or 90° from the north-south line, which is the same thing. Now, if my needle showed the Sun rising in the equinoctial line of my dial, when it should have indicated 7° 50′ to the north of that line, it follows that these 7° 50′ represent the northwesting of the needle; and thus the results derived from this method of determining the northwesting agree with those I obtained by the method of arc-differences; from which it may be concluded that the opinion of those is false who claim that in the equinoctial day the Sun rises exactly east of their needles, for in no case whatsoever can this happen because they generally vary **[8]**.

Notes by the translator on excerpts, Lisbon to Goa, 1538

The translated excerpts above were checked with the complete text of the "Roteiros de D. João de Castro (3 vols., 2nd edition, 1940, published by the Agencia Geral das Colonias, Lisbon, Portugal), a reproduction of the two only known copies (the original by J. de Castro is lost), belonging to the public library of Evora.

This valuable and reliable edition has a preface and numerous annotations by Commander A. Fontoura da Costa, author of the equally important and authoritative treatise "A marinharia dos descobrimentos" (2nd edition, 1939).

Some of the notes made by Fontoura in his Volume I are given in this English version together with numbers given by Fontoura and are indicated in the above translation by bold-face type as

[1] Note 12: D. João de Castro gave the name "dial-plate and shadow-instrument" to the instrument (dial-plate) invented by Pedro Nunes, to determine, at sea, the shadow (opposite to the azimuth) of the Sun.

[2] Note 13: The author in saying "if the needles varied or not," meant if they varied in their swings to northeast or to northwest. At the same time, the expression "variation of the needle" was not known with the meaning of later centuries; probably it originated from variation to northeast and to northwest. As ships were built of wood the needles were free from local disturbing influences; for this reason the compass-variation coincided with the magnetic declination.

[3] Note 14: That is, the needle's meridian coincided with the meridian of the place; the needles did not deviate to northeast or northwest.

[4] Note 15: Pedro Nunes, in his "Treatise of the sphere," indicated two ways for the determination of the pole's altitude (latitude) at any hour of the day, both based upon azimuth, altitude, and declination of the Sun.

[5] Note 26: The author proves, thus, that the agonic meridian did not run between the Canary Islands.

[6] Translator's note: That is, approximately 1/4, for one point represents 11-1/4°.

[7] Note 99: The first land of Natal, located at 32° south, corresponds to Mesquita Perestrelo's First Point (of Natal), with the same latitude. We believe this point to be Cape Morgan (32° 40′ south, 28° 23′ east). The needles here suffered no northwesting or northeasting in 1538.

[8] Note 142: The author criticizes those who claim that in the equinoctial line (no declination) the Sun rises and sets exactly east and west, when this can happen only when there is no northeasting or northwesting of the needle.

First journey along the coast of India, 1538-1539

Of the property inherent in two rocks of this little Island (of Chaul)—Walking around this little island, and going up the hill on its northern side, in order to see and sketch the position of other surrounding small islands and plains, a wonderful thing happened to me; and it came about this way. Placing the needle on top of a big boulder so as to get an idea of the bearings of the island, suddenly the rose turned the north to where the south was at the beginning. When I saw this, and thinking it was due to a displacement of the rose, I lifted the instrument off the boulder to set in order, but in so doing the north end returned to its right place. As it occurred to me that such a strange fact was due to the quality and nature of the rock, I repeated the observation several times, placing and removing the instrument. Greatly surprised at this occurrence I went over the greater part of the hill, placing the needle on all boulders and pieces of salient rock, but none gave any deviation; I found only one other of similar nature to the first, in which the rose, however, did not make as great a turn; but sighting on any object at northwest by west, this same object would lie to the southwest when the needle was placed on the boulder; that is, it indicated a sudden variation of seven points; but the first boulder mentioned gave almost double this value, for, away from it, the object at northwest by west, changed to south by east when the needle was placed on it, which means a variation of twelve points. This extraordinary change was not only observed when the needle was placed on the boulder, but also when simply held above it.

The argument does not hold that these boulders were of a kind of loadstone, as fragments cut from them and brought near the needle would show, thereby moving the rose of the *fleur de lis*, because I saw an experiment to the contrary, in which many pieces, small and large, brought near the north end of the needle and carried around the whole circumference of the rose, failed to move the latter, the *fleur de lis* remaining still. Moreover, if these boulders were of the nature of a loadstone, they certainly should attract iron and steel, but they have not this property because I made all kinds of experiments with pieces of iron, sewing needles, and other articles of steel which are necessary in such proofs. Therefore no argument is good and acceptable; but this doubt like the other with the small island Nagam, is up to Apolo's decision [**1**].

It is to be noted that these boulders have the following aspects. The first one, with which the needle varied the most, is slightly grooved with a kind of a hole in the center; and the second has several fissures

that run all around the boulder; and both are very near each other, and lie in the flat crown of the hill on the north side, next to the open gully that runs along the ridge.

Note on the substitution of the needle of my instrument—Considering that avowal and honesty are greatly necessary in matters submitted to and under the jurisdiction of the mathematical arts, I declare herein that after arriving in India and reaching Goa, the small needle of my instrument was lost—the one made by the eminent Joham Gonçalves [**2**]; searching then for many others, from watches, and having some made, none was satisfactory until by chance I found one that belonged to a German watch, very long and light, and which brought me much contentment, and to place it immediately in the instrument I employed the following procedure: Before magnetizing this small needle I placed it on the pivot and socket where it should swing, straightening it along the meridian-line of the dial-plate, and taking note where the shadow of the style cut the circle, and promptly removed it, and the pilot magnetized it; after it was magnetized I replaced it, and straightening it as before, with the meridian-line or the north-south of the dial-plate, the shadow of the style cut the circle in the same point it was cast at first before its magnetization.

This made me very thoughtful, for the watch from which I removed the needle was made in Germany, where certainly the needle was magnetized with the loadstones of that country; the stone now used by the pilot to remagnetize the needle was from this coast of India, and despite the fact that the regions are so different the property of the loadstones seems to be one and the same [**3**].

Annotation—In these sets of observations made from December 13 to date, that is, December 23, I think there are two things to be noted. The first is that being in the Rio de Paguode de Baçaim, I found through four sets of observations, made in one day, that the needle of my instrument northwested 10-1/4°, these observations being carried out with great care and all of them in the presence of Doctor Lois Nunes, the vessel remaining so steady that the style's shadow did not move to either side. Now finding myself in this estuary of the Baçaim, where I have made so many observations, all of them indicated a northwesting of the same needle 12-1/2°, and as on the first day this difference surprised me considerably, I did not approve it until many other determinations were made, which was done on three successive days, and on all of them I found that the afternoon arc was greater by 25° than the forenoon one; half of them is 12-1/2°, the value of the northwesting of the needle in this river's mouth.

This is obviously a very high value for such a small distance, the needle making so great a difference in one and the same meridian; and if by chance it be argued that I and the Doctor erred in the determination of the difference in the arcs when, together, we made the observations in Rio do Paguode, I say that it would not be likely for us to go wrong in four sets of experiments, making the same mistake in all of them successively, for in all of them we found the afternoon arc 20-1/2° larger than the morning one. I cannot think of any reason to explain this, except that I made the observations very close to land, in whose vicinity existed rock and boulders, which were likely of the same kind and nature

of the loadstone, that is, of ferrous composition, and therefore capable of attracting to them the iron of the needle, deflecting the latter from its natural position [**4**].

Amplitude of sunrise at Baçaim Bar

On December 24, 1538, the Sun rose almost 37° from east to south; the style cast its shadow at another 37° from west to north. And according to needle A, the Sun rose directly at east-southeast.

At the same time, according to needle B, the Sun rose at southeast by east. And bringing out another needle of the pilot, which may be called C, it was found that according to it, the Sun rose between south and south by east, a little closer to the former.

Just before sunset, the style's shadow fell on a round number of 13°, reckoning from east to north.

And according to needle A the Sun disappeared at west-southwest. However, in accordance with needle B, sunset occurred at west by southwest.

At the same time the needle C showed the Sun setting between west and west by south, a little closer to the former. From which it follows that the needle northwests almost 1-1/2 points.

Annotation—Finding such disparities in the three needles, I supposed these differences might be produced by the iron mountings of the needles being deflected from the north and *fleur de lis*, as often happens and the needles have to be corrected for their variation. I therefore opened them all, and saw clearly their mountings, finding them in order and strictly adjusted to the north and the *fleur de lis* of the needles. This doubt having been removed, another was brought up, as it seemed to me that these three needles were magnetized by loadstones of different kinds, each needle assuming the virtue and property of the stone used, but inquiring of the pilot on this misgiving, he swore to me that all the three needles were magnetized with a single loadstone, and immediately, in my presence, he magnetized the three needles again, and they behaved as before. This fact suggested to me that the variation observed in the needles is caused by ferrous matter and not by the nature of the loadstone, and that in accordance with the quantity of steel in the iron, the *fleur de lis* of the needle will tend to its natural position.

Sunrise—On January 10, 1539, the Sun being in the first point of Aquarius, as it rose on the horizon, the style's shadow fell on 33° from west to north, therefore on this day the Sun rose 33° from east to south.

According to needle A, however, the Sun rose at east-southeast, 4° to east more or less in my estimate and that of the pilot.

And according to needle B, the Sun rose at southeast by east, more or less 4° to east.

And thus in accordance with needle C, the Sun rose between southeast and southeast by east, closer to the latter. I measured this amplitude of sunrise when north of the small islands, nearly a league out at sea.

While I was making these observations, the pilot held the astrolabe in his hands ready to note in his instrument the rising Sun over the high land on shore, finding that it rose 1-1/2° above the horizon.

On this same date, January 10, I was anchored on account of a steady northwest wind all day, making the following sets of observations.

First observation before noon

The Sun being in altitude 30°, the gnomon's shadow read 42°, approximately, reckoning from north to west.

Second observation before noon

Sun's altitude 35°, shadow 36-1/2°, reckoning in the same way from north to west to the point or degree of the circle where the style's shadow fell.

Third observation before noon

Sun's altitude 40°, shadow 31-1/2°, reckoning from north to west.

First observation after noon

Sun's altitude 40°, shadow 53-1/2°, reckoning from north to east.

Thus in this set of observations the afternoon arc was greater than the morning one by 22°; half of these is 11°, which is the amount the needle northwests in this place.

Second observation after noon

Sun's altitude 35°, shadow 59°, reckoning from north to east.

Thus, in this set of observations, the afternoon arc was greater than the morning one by 22-1/2°; half of which value is 11-1/4°, the amount the needle northwests in this place.

Third observation after noon

Sun's altitude 30°, shadow 63-1/2°, reckoning from north to east,

Thus, in this set of observations, the afternoon arc is greater than the morning one by 22°, half of which value is 11°, the amount of northwesting of the needle in this place.

Sunset—Just before sunset, the style's shadow fell on 11°, from east to north, or 79° from north to east, which is the same thing; from which it follows that the Sun disappeared at 11° from west to south.

Thus, in this set of observations, comparison made with those of sunrise, the afternoon arc is greater than the morning one by 22°, half of which value is 11°, the amount the needle northwests in this place.

According to needle *A*, however, sunset was indicated at west-southwest, and in the pilot's estimate as well as my own, it occurred at 4° towards the west.

Thus, if we consider sunrise and sunset as given by this needle, we will find the afternoon arc equal to the morning one; from which it follows that the needle sought directly the true poles of the world.

According to needle *B*, sunset occurred at west by southwest, in my estimate perhaps 2° or 3° towards the west.

Thus, based on this needle's indications of sunrise and sunset, we shall find the afternoon arc greater than the morning one by two points; half of this is one point, the amount the needle northwests, as given by this and the previous sets of observations in which it was employed.

Now, with needle *C*, the Sun disappeared at west by southwest.

Thus, with this needle, the afternoon arc was greater than the morning one by almost three points if we take into consideration the sunrise; half of this value is approximately one point and a half, which is the

amount of this needle's northwesting—in this set of observations and in the previous determinations made with same.

Corollary—From these sets of observations which I made today, January 10, 1539, and which showed me that the needle of my instrument northwests 11°, we conclude that in one and the same meridian, the needle can northwest and northeast more or less [**5**], which fact is demonstrated by the following: In the Paguode de Baçaim Island I found that this needle's northwesting was 10-1/4°, and in Baçaim, 12-1/2°, and now, as far along as these islets of Dabul, the northwesting amounts to 11°, the three places being on the same meridian; from which we are justified in supposing that such variations are caused by particular and inherent mysteries concealed by mighty Nature in its vast and secret workshops [**6**].

Notes by the translator on excerpts, first journey along the coast of India, 1538-1539

We refer the reader to the remarks (introductory) made at the end of the extracts from log-book, Lisbon to Goa, 1538. Some of the notes made by Fontoura in his Volume II are given in this version, his numbers following numbering of our notes indicated in bold-face type.

[**1**] Note 75: D. João de Castro solved the problem later [see **6**].
[**2**] Note 94: This is the shadow-instrument referred to in log-book I, Lisbon to Goa, 1538.
[**3**] Note 96: D. João was right.
[**4**] Note 105: D. João de Castro, in the first part of his important annotation of December 23, 1538, declares that he made accurate observations with his needle (shadow-instrument), obtaining:
(*a*) Mouth of river Paguode de Baçaim, December 13, 1538
Needle northeasts . . . . .10-1/4°
(*b*) Mouth of river Baçaim, December 21-23, 1538:
Needle northwests. . . . . .12-1/2°
(*a-b*) Difference . . . . .22-3/4°
which is found "very large," considering the two mouths are (approximately) in the same meridian and separated by a small distance (17 maritime miles of our time).

Translator's note: Here, Fontoura made a slip, writing "northeasts," instead of "northwests." The results of the observations at the mouth of river Paguode de Baçaim are given by D. João de Castro several times in the log-book as northwest variation, and not northeast. The observations themselves prove it.

In consequence of this inadvertency, the difference given above by Fontoura, in his note 105 (22-3/4°), is naturally wrong and much exaggerated. The true difference, according to the navigator's figures is 2-1/4°, and within the northwest sector, large enough, in 17 miles, to surprise D. João de Castro.

Fontoura's Note 164 [**6**] of the translation, referring again to the case, confirms our finding of his oversight. In this Note he explains that the differences in "northwesting of the needles are not great." Obviously, this small mistake does not diminish the importance of the conclusion of his Note 105.

He relates the great difference to the fact of having made the last

observations "very close to land, in whose vicinity existed rock and boulders," which, constituted of ferrous matter, "attracted to it the iron of the needle, deflecting the latter from its natural position." The doubt raised at the Chaul Islet (Note 75), which was of the same nature, is now solved by D. João de Castro himself.

Thus was discovered the local attraction, which only centuries later was observed by foreigners.

This important point of the log-book was indicated for the first time by G. Hellmann.

[5] Translator's note: That is, in one and the same meridian, the northwesting or the northeasting, given by the needle, may vary in magnitude.

[6] Note 164: The differences in the northwesting of the needles are not great in these three places, especially if we keep in mind that their latitudes are 105 maritime miles apart; extreme longitudes are separated by 20′ only.

From India to Suez, 1541

On March 7, 1541, being in Çuaquem, I went on shore in the morning, and set up my instrument on a very low hill, and, without moving it elsewhere or touching it, I made the following sets of observations.

First observation before noon

The Sun being in altitude 38-1/6°, the style's shadow fell on 70°, reckoning from north to west.

Second observation before noon

The Sun's altitude 50°, style's shadow 60-1/2°, reckoning from north to west.

Third observation before noon

Sun's altitude 55°, style's shadow 55°, reckoning from north to west.

First observation after noon

Sun's altitude 55°, style's shadow 57-1/2°, reckoning from north to east.

Thus, in this set of observations, the afternoon arc was greater than the morning one by 2-1/2°, half of which value is 1-1/4°, that is, the needle's northwesting in this place.

Second observation after noon

Sun's altitude 50°, style's shadow 63°, reckoning from north to east.

Thus, in this set of observations, the afternoon arc was greater than the morning one by 2-1/2°. Half of this is 1-1/4°, which is the amount of northwesting of the needle in this place.

Third observation after noon

Sun's altitude 38-1/6°, style's shadow 72-1/2°, reckoning from north to east.

Thus, in this set of observations, the afternoon arc was greater than the morning one by 2-1/2°, and half of this is 1-1/4°, which is the amount of northwesting of the needle in this place.

LIST OF GEOMAGNETIC OBSERVATORIES AND THESAURUS OF VALUES†—VI

By J. A. Fleming and W. E. Scott

Table 1—*Annual values of geomagnetic elements at observatories*—Continued

Observatory	Latitude, +=N −=S	Longitude, east	Year	Declination, D	Inclination, I	Components of intensity: Horizontal, H	North, X	East, Y	Vertical, Z	Total, F
*Corrections and additional results received since publication of Parts I to V***										
	° ′	° ′		° ′	° ′	γ	γ	γ	γ	γ
Baie Tichaja[2] (Calm Bay)	+80 20	52 48	1932 1933 [i]	+21 07.3	+83 06.3	6605	6159	+2380	+54616	55000[j]
Refuge Harbor[2]	+78 32	287 37	1923 1924 [k]	−99 49.5	+85 47.1	4136	706	−4075	+56118	56270
Cape Thordsen[2] (Spitzbergen)	+78 28	15 42	1882 1883 [l]	−12 42.4	+80 28.2	8903	8685	−1958	+53031	53774
			1932 1933 [m]	− 5 54.6	+81 12.4	8187	8144	− 843	+52926	53555
Sveagruvan[2] (Spitzbergen)	+77 54	16 45	1932 1933 [n]	− 4 53.7	+80 59.4	8328	8298	− 711	+52524	53180
Bear Island[2] (Björnöya)	+74 29	19 14	1932 1933 [o]	− 1 53.9	+79 34.1	9498	9493	− 315	+51588	52455
Dickson[2]	+73 30	80 25	1932 1933 [p]	+28 31.6	+83 04.8[q]	6986	6137	+3336	+57486	57908
Matochkin Shar[2]	+73 16	56 24	1932[r]	+21 36.9	+80 28.1	9103	8463	+3353	+54216	54975
			1932 1933 [s]	+21 38.6	+80 28.7	9093	8452	+3354	+54218	54974
			1937	+22 14.0	+80 38.3	8962	8296	+3391	+54358	55092
			1938	+22 21.9	+80 39.6	8935	8263	+3400	+54325	55055
			1939	+22 29.5	+80 40.1	8924	8245	+3414	+54309	55037
Scoresby Sund[2] (Greenland)	+70 29	338 02.3	1932 1933 [t]	−34 33.2	+78 17.9	10576	8710	−5998	+51063	52147
Kandalaksha[2]	+67 09	32 26	1932 1933 [u]	+ 6 44.0	+76 11.7	12318	12233	+1444	+50118	51609
College[2]	+64 52	212 11	1932 1933 [v]	+30 25.6	+77 14.6	12572	10841	+6367	+55530	56935
			1941[w]	(+29 53.7)	(+77 13.0)	(12564)	(10892)	(+6262)	(+55376)	(56783)
			1942	(+29 52.4)	(+77 11.2)	(12582)	(10910)	(+6267)	(+55323)	(56736)
			1943	(+29 50.1)	(+77 12.2)	(12572)	(10906)	(+6255)	(+55350)	(56760)
Bowdoin Harbor[2] (Baffin Island)	+64 24	282 08	1921 1922 [x]	−52 12.1	+85 29.2	4722	2894	−3731	+59824	60010
Chesterfield Inlet[2]	+63 20	269 18	1932 1933 [y]	−12 36.1	+86 23.4	3834	3742	− 836	+60762	60883
Fort Rae[2]	+62 39	244 16	1882 1883 [z]	+40 22.6	+82 56.5	7650	5828	+4956	+61778	62250
Fort Rae[2]	+62 50	243 56	1932 1933 [a]	+37 30.7	+82 39.0	7734	6135	+4709	+59956	60453
Jakutsk[2]	+62 01	129 43	1933[b]	−16 13.4	....	.....	.....	......	....	.....
Potsdam[2]	+52 23	13 04	1926	**	**	18503	**	**	**	**

†Continued from Terr. Mag., **48**, 97-108 (which see for numbered footnotes), 171-182, and 237-242 (1943), **49**, 47-52, and 109-118 (1944).

**Corrected values are indicated only for the particular element concerned; double asterisks (**) in column indicate values as previously published are correct.

[i]Polar Year, August 1, 1932, to August 31, 1933, for H and Z, and September 1, 1932, to August 31, 1933, for D. [j]The value of F is as given by the report on results at Observatory; computed value of F from values of H and Z is 55014γ. [k]Nine months of D, H, and Z, October, 1923, to June, 1924. [l]First Polar Year, August 23, 1882, to August 23, 1883. [m]For practical, as well as economical, reasons, Sveagruvan was chosen as the station in Spitzbergen for the Polar Year of 1932-33 instead of Cape Thordsen and the values given for Cape Thordsen for September 1, 1932, to August 31, 1933, are dependent on those at Sveagruvan during Second Polar Year and comparative measurements at Cape Thordsen in August 1933. [n]Polar Year, September 1, 1932, to August 31, 1933; see also [m]. [o]Polar Year, October 1, 1932, to August 31, 1933. [p]Polar Year, December 1, 1932, to August 31, 1933, for D and H and March 1 to August 31, 1933, for Z. [q]The value of I is as given by the report on results at the Observatory; the computed value of I from values of H and Z is +83° 04′.3. [r]Five months, August to December, 1932. [s]Polar Year, August 1, 1932, to August 31, 1933. [t]Polar Year, December 1, 1932, to July 31, 1933. [u]Polar Year, September 1, 1932, to August 31, 1933, for D and H, and December 1, 1932, to August 31, 1933, for Z. [v]October 1, 1932, to March 31, 1934 (Polar Year station, 1932-33); the values of Z have an uncertainty of ±50γ. [w]The station was occupied from August 1, 1941, and is slightly removed from the Polar Year station of 1932-33. [x]Seven months December 1, 1922, to June 30, 1922. [y]Polar year, September 1, 1932, to August 31, 1933. [z]First Polar Year, September 1, 1882, to August 31, 1883. [a]Second Polar Year, September 1, 1932, to August 31, 1933. [b]Six months, March to August, 1933.

TABLE 1—*Annual values of geomagnetic elements at observatories*—Continued

Observatory	Latitude, +=N −=S	Longitude, east	Year	Declination, *D*	Inclination, *I*	Components of intensity: Horizontal, *H*	North, *X*	East, *Y*	Vertical, *Z*	Total *F*
	° ′	° ′		° ′	° ′	γ	γ	γ	γ	γ
Niemegk[2]	+52 04	12 40	1939	− 4 18.3	+66 58.5	18438	18386	−1384	+43386	47141
			1940	− 4 09.6	+67 00.1	18434	18385	−1337	+43431	47181
			1941	− 4 01.4	+67 01.9	18430	18385	−1293	+43484	47228
			1942	− 3 53.8	+67 02.6	18433	18390	−1253	+43516	47259
			1943	(− 3 46.3)	(+67 03.2)	(18436)	(18396)	(−1213)	(+43546)	(47288
Capodimonte	+40 52	14 15	1922	c	c	c	c	c	c	c
Coimbra[1]	+40 12	351 35	1934	**	**	23280	22649	−5383	+36807	43551
Cheltenham[2]	+38 44	283 10	1943	(− 7 06.3)	(+71 21.7)	(18182)	(18042)	(−2249)	(+53908)	(56892
San Miguel*,[d] (Ponta Delgada)	+37 46	234 21	1911	−19 56.0	+60 59.1	22993	21615	−7839	+41456	47405
			1912	−19 52.3	+60 53.9	23028	21657	−7828	+41371	47347
			1913	−19 47.9	**	**	21696	−7810	+41302[e]	47303
			1914	−19 44.1	**	**	21708	−7788	**	**
			1915	−19 40.6	+60 43.4	23069	21722	−7768	+41148[e]	47173
			1916	−19 37.4	**	**	21732	−7748	**	**
			1917	**	**	**	21756	−7729	**	**
			1918	**	**	**	21768	−7702	**	**
			1919	**	**	**	21792	−7678	**	**
			1920	**	**	**	21819	−7656	**	**
			1921	**	**	**	**	**	+40632[e]	46755[e]
			1922	**	+60 16.9	**	**	**	+40624[e]	46776[e]
			1923	**	**	23205	21929	**	**	**
			1924	−19 01.6	**	**	21975	−7578	+40462[e]	46664[e]
			1925	**	**	**	**	**	+40362[e]	46583[e]
			1929	**	**	**	**	**	+40049[e]	46338[e]
			1930	**	+59 46.6	**	**	**	+40013[e]	46308
			1933	**	+59 35.3	**	**	**	+39822	46175
			1938	−17 44.2	+59 19.0	23479	22363	−7153	+39571	46012
			1939	−17 39.8	+59 15.3	23524	22415	−7138	+39547	46014
			1940	−17 37.7	+59 13.4	23538	22433	−7128	+39523	46001[e]
			1941	−17 31.1	+59 12.2	23568	22475	−7094	+39541	46031
			1942	−17 25.4	+59 07.0	23635	22551	−7077	+39517	46045
San Fernando	+36 28	353 48	1942	−11 03.3[2]	+52 55.5[1]	25430[2]	24958	−4876	+33655	42182
Kakioka	+36 14	140 11	....	f	f	f	f	f	f	f
Honolulu[2]	+21 19	201 56	1943	(+10 26.6)	(+39 10.2)	(28413)	(27942)	(+5150)	(+23149)	(36649)
Samoa, Apia[2]	−13 48	188 14	1937	**	**	34960[g]	34353[g]	+6486[g]	−20641[g]	40599[g]
Toolangi[1] (Succeeding Melbourne)	−37 32	145 28	1938	+ 8 48.0	−67 50.2	22895	22625	+3503	−56205	60689
			1939	+ 8 51.0	−67 49.8	22910	22637	+3525	−56223	60712
Amberley[2]	−43 10	172 44	1941	**	−68 04.1	**	**	**	**	**
Kerguelen[2]	−49 25	69 53	1902[h]	−36 58.0	−70 25.3	16243	12978	−9768	−45672	48474
			1903[i]	−36 57.8	−70 22.4	16261	12993	−9778	−45598	48411
Laurie Island[2] (Oreadas)	−60 43	315 13	1932, 1933[j]	+ 3 07.8	....	23928	23892	+1307	....	.....
Winter Station, *Gauss*[2]	−66 02	89 38	1902[k]	−62 22.6	−77 07.2	13309	6171	−11792	−58206	59708
			1903[l]	−62 16.2	−77 05.1	13347	6210	−11814	−58204	59715

[c]The values entered for Capodimonte for the year 1922 on p. 180 of **48** (Part II of the Thesaurus) are to be deleted as they were erroneously entered; they apply for a field-station at Montecassino for epoch 1922.7. [d]Values of *D* beginning with 1917 derived from magnetograms; values of *D* from 1911 to 1916 and of *I*, *H*, *Z*, and *F* throughout derived from absolute observations only but the original values of *D* so obtained have been adjusted to the series of values obtained from magnetograms by application of a correction of +5′.3 which was found to be the average difference between values of *D* from absolute observations and those obtained from magnetograms for any subsequent year. [e]Values so marked are as calculated from the observed elements and differ by 2γ or more from values supplied by the Observatory. [f]The last sentence of footnote [i] on p. 239 of **48** (Part III of the Thesaurus) should read: "In 1916 it was found that absolute values at Tokyo were approximately obtained from those at Kakioka by applying the following corrections: +5′.54 for *D*, +264.7γ for *H*, and −481.4γ for *Z*"; these corrections are in the sense of signs adopted in this Thesaurus, namely, + for *D* east, for *H*, for northerly *I*, and correspondingly for the intensity-components, all as referred to the north-seeking end of the needle. [g]In 1937 absolute observations of *H* were made without mounting the counterpoise-weight on the deflection-bar; it was later found that when counterpoise-weight was properly mounted the resulting value of *H* was 21γ greater than when it was not used; the value of *H* for 1937 and of the intensity-components for that year then are as here indicated. [h]Nine months, April to December, 1902. [i]Two months, January and February, 1903. [j]Polar Year, August 1, 1932, to August 31, 1933. [k]Eight months, May to December, 1902. [l]One month, January, 1903.

The next parts of this series will summarize, within the limits of available published material, magnetic values obtained at observatories during the 19th century and at short-period recording stations of special expeditions, except for those data already shown in Table 1. Because of limitations of earlier facilities, such as inadequate instrumental equipment and control-observations and the fact that much of the older work was done before the introduction of photographic recording, the data will not be, in general, of the order of accuracy later attained. They do give, however, further invaluable material for secular-variation determinations.

Some comments on the improvement of recording and reduction of data at magnetic observatories

The compilations so far made for this Thesaurus have emphasized certain aspects of procedure for, and control of, operations at magnetic observatories. It is thought that comments on several of these items may be of immediate interest to organizations and personnel concerned with geomagnetic investigations.

There is some literature on the quantity, that is, distribution of magnetic observatories, but there appears to be a real lack of material dealing with the quality. One is fully aware that the standards of accuracy prescribed for magnetic measurements are difficult ones to meet and call for eternal vigilance and patience on the part of those undertaking them. Although the required precision is not always obtainable, it is felt strongly that as near perfection as possible is well worth striving for. It is further believed that with certain precautions always in mind it is as easy to obtain good results as to obtain poor ones.

In assembling and computing the magnetic elements for this Thesaurus many apparently anomalous results were discovered even on cursory examination. When monthly and annual values were studied more carefully for secular-variation purposes and use in the reduction of magnetic observations to epoch, oftentimes quite glaring inconsistencies were uncovered and omissions noted.

That nothing is stronger than its weakest link is never so true as when applied to the recording of magnetic values at observatories. Almost everyone is cognizant of the many pitfalls to be encountered in the operation of a magnetic observatory; not so generally known is that the results from some observatories demonstrate clearly that these have not always been avoided. These comments are made in an entirely constructive and not critical spirit. Poor results must be attributed most frequently to remissness in one or more of the following failures of effective control.

(1) Location of observatory is not well removed from any local disturbances, either natural or artificial.

(2) Instrumental equipment (both absolute and variation) is not constructed of non-magnetic materials.

(3) Instrumental constants (especially deflection-distances, moment of inertia, and temperature- and induction-coefficients) are not determined accurately at the outset of operation, and are not corrected periodically, for any change in moment of inertia or the magnetic moment of the oscillation-magnet.

(4) Variation-magnets are not properly orientated (D in the meridian, H in the prime-vertical, and Z in the horizontal plane).
(5) Scale-values of variometers are not carefully determined and do not cover records at all times, particularly at times of changes in trace.
(6) Base-line determinations (absolute observations) are not adequate and accurate.
(7) Adjustments to variation-instruments are not made with forethought and care, to insure minimum loss of trace.
(8) Observatory-records are not computed and reduced promptly.
(9) When it is necessary to observe elements on more than one pier, investigation and determination of possible station-differences are not made.

It is believed that if the personnel at many observatories would keep in mind these briefly stated fundamentals, magnetic results would show much improvement.

It is important that accurate determinations be made of possible systematic errors and corrections for the standard instruments at different observatories. It is probably more important as regards the scientific use of data accumulated by observatories that constancy of absolute standards be maintained. There are many excellent reasons that whenever possible, and so far as possible, intercomparison of instruments by observers at observatories and visiting observers, with interchange of stations and instruments, should be made. Experience has indicated emphatically that contact of observers is invariably helpful in ironing out difficulties and differences of procedure and at the same time is of mutual stimulating value in the interchange of ideas. Questions such as the exchange of stations and of instruments are vital in such intercomparisons; thus significant differences of the three magnetic elements at individual piers often exist and should be determined to make for homogeneity.

While horizontal intensity is the element requiring particular control, it is necessary, in view of the many different types of instruments and methods used at various observatories, that definite controls be had for vertical intensity, to a considerable extent for inclination when vertical intensity depends upon inclination as determined by an inductor and especially if a dip-circle is used, and to a lesser degree for declination. Earth-inductors are not always kept in proper mechanical adjustment; at times meridian-settings are inaccurately made. Dip-circles have always been and, under the circumstances of their mechanical design, must *always* be uncertain—indeed, whenever possible, the dip-circle should be abandoned for any control in observatory-work. While *theoretically* earth-inductors (but not dip-circles) and declination-instruments can be adjusted to zero-correction by a skillful physicist, there is not always appreciation of the need of adjustment and there is very frequently disinclination to attempt any adjustments. Frequently instruments, even those by the best manufacturers, do contain magnetic impurities which are not found by the observer since he usually places his reliance upon the reputation of the manufacturer and feels that there can be no question regarding the non-magnetic quality of the materials used.

The necessity of effective control in inclination or vertical intensity is

readily apparent from the relationship between the three elements expressed by

$$\triangle Z = \tan I \triangle H + H \sec^2 I \triangle I$$

where Z and I represent vertical component of the Earth's field and angle of inclination, respectively. Thus for an error on standard of 1′, that is, $\triangle I = 1'$, typical equivalent errors of $\triangle Z$ are: Cheltenham 55γ; Watheroo 38γ; Huancayo 8γ. The need for control in inclination is evidenced by results of comparisons at one of our principal observatories where a modern earth-inductor and methods are used and for which the standard of the observatory gave a correction of $+1'.1$ on International Magnetic Standard in I.

Four precautions must be taken when magnetometric methods of observation are used for the control of constants. These are: (1) Redeterminations of moment of inertia of the magnet-system from time to time to control changes due to oxidation and wear of the magnet as well as of its suspension-arrangements; (2) suitable provision to protect the deflecting magnet during observations of deflection and also to protect the deflection-bar against sudden or irregular changes of temperature; (3) means by which the effective deflection-distances may be invariable for the same instrument; and (4) progressive change in the magnetic moment of the oscillation-magnet and concomitant change in correction for induction.

Examples of changes in inertia which are typical of the majority of the results obtained for magnetometric instruments are indicated in the following summary for four extensively used magnetometers of the Department of Terrestrial Magnetism. Many cases have been found through intercomparisons at observatories which reflect lack of adequate control of moment of inertia.

Magnetometer No.	Interval between comparisons in years	Observed differences from earlier to later comparisons	
		Observed correction on IMS	Observed change in inertia
9	4.3	$-0.00058H$	$-0.00064H$
13	12.7	$-0.00090H$	$-0.00078H$
24	2.8	$-0.00106H$	$-0.00094H$
27	1.2	$-0.00006H$	$-0.00008H$

The evidence of such results certainly is positive and may be taken not only as confirmation of actual change in inertia but also as indication that no essential changes had taken place in the other constants concerned in determinations of intensity for the respective instruments.

Uncertainties must be reduced to a minimum during observation as regards temperature-readings and especially as regards any lag of temperature. Thus, for most magnetometers, uncompensated differences of 0°.2 C in temperature produce quite appreciable differences in the resulting values of the distribution-coefficients as determined from observations at three deflection-distances.

While it is usually the practice to make dimensions of short and long magnets of magnetometers such that theoretically the value of the first

or of the second distribution-coefficient would be zero, it is found in practice that the coefficients differ from the theoretical values. Thus for instruments in which the second coefficient should be theoretically zero the first coefficient is generally different from the theoretically calculated value—often as much as five or ten per cent—while the second distribution-coefficient often has a sensible value. In general the use of an equivalent coefficient for the two distribution-coefficients meets all practical requirements both in the field and observatory within the limit of accuracy which may be reasonably expected by the magnetic method, namely, about $0.00015H$. It therefore appears that, for magnets made of high-grade homogeneous magnet steel and properly treated when originally magnetized, the distribution-coefficients, assuming ordinary care in transportation and in handling, are sensibly constant over long periods.

As with the magnetometer, the constants of the electromagnetic instruments and of their appurtenances must be carefully controlled. Thus there is possible change with time of the electromotive forces of the standard cells used, particularly for the non-saturated type of cell. After one year's use of three unsaturated standard cells with the sine-galvanometer at the Cheltenham Magnetic Observatory, calibrations by the National Bureau of Standards showed that the electromotive forces of all had decreased seven parts in 100,000, making necessary a correction to the values of horizontal intensity originally computed of about -0.1γ per month; in view of the great accuracy of electromagnetic determinations, this constitutes an important correction within three or four months. With the saturated types of standard cells there is less danger of such change but, on the other hand, temperature-changes must be very carefully controlled. Other tests and calibrations should be made from time to time to check against possible changes in the resistance of the coils of the instruments and of the standard resistances used.

While the corrections of declinometers with collimating optical systems theoretically may be made entirely negligible, there is ample evidence that declination-standards should be checked by intercomparisons wherever possible. Thus there may be magnetic material in the instrument itself which causes an incorrect value. For example, at one observatory a correction on standard of nearly $3'$ was found; at another an indicated error of several minutes of arc because of erroneous azimuth was corrected only after intercomparisons had shown such serious disagreement.

It may be helpful to enumerate in detail some difficulties encountered. The Earth's magnetism has certain regular changes—diurnal, seasonal, annual, secular, sunspot-cycle, lunar—as well as irregular changes at times—storms, perturbations, and pulsations. Often there are recorded irregular changes caused by mechanical maladjustments, introduction of magnetic material in or near instruments, unrecorded readjustments, and the like. In some cases, irregular changes indicated by records or tabulations are hard to accept and more so when no comment or explanation is offered to account for significant irregularities.

Failure to obtain accurate absolute observations occasions subsequent difficulty in the choice and adoption of base-line values, and lack of good judgment in this respect impairs the results. The personal equation of observers arises at times, and to mitigate this condition

observers should alternate whenever possible, not only in the case of absolute observations but also in intercomparisons or standardizations.

The adoption of the Helmholtz-Gaugain coil method of obtaining scale-values for the variometers is urged. Once installed, the simplicity of measurement by this method will go far toward insuring better control of records. The use of an auxiliary scale-value deflector-magnet often occasions shifts in trace which are difficult or impossible to detect.

Much as various businesses plot their progress as to sales, etc., it is suggested that, for better control of scale-values and base-lines, as these are obtained, they be plotted on an ample scale, say, one millimeter per gamma. Such graphs indicate immediately the caliber of results to be expected. Observers will say that absolute accuracy is impossible, which of course is true. Base-line values often do show considerable variation —doubtless in part attributable to instrumental behavior. How closely the adopted base-line values should correspond to those resulting from observation can be learned only from experience. Anyone who has had this experience, however, knows that there should be orderliness and logical progression in the results. It is felt that the arduous and continuous task of reducing magnetograms would be greatly lightened were these sign-posts on the road to good results looked for and their guiding qualities utilized. In the case of one observatory—an extreme case—a range in base-line values of 350 gammas in one year was noted; obviously the results were not good.

Reliable long-period observations are fundamental requirements in geomagnetic investigations. Often, however, the usefulness of results is impaired by abrupt discontinuities occasioned by change of site, change of instruments, or shut-down for repairs. When observatories are moved to new locations, observations should overlap for a year or more at old and new sites. Many observatories fail to give full and adequate explanations of abrupt changes in results. Every control must be made to reconcile all results with those of preceding years.

Many of the annual values lack homogeneity in the basic values of D, H, and Z or I. For example, an observatory may obtain complete recording of D for one year, but only ten months of H (January to October, 1940, say), and eight of Z (January to August, 1940). In such a case, while all the results should be published, it would be better to derive values of the seven elements and intensity-components by using the number of months during which records were obtained in all recording; thus in the above example, for the eight months, January to August, 1940, that is the epoch 1940.3. Certainly, when observatories compute values for incomplete years of observed results, note should be made of what values were used.

As regards the selection of new sites for observatories, the future may prove that greater consideration should be given to surrounding topography (apart from local disturbance). Knowledge gained in magnetic prospecting, involving geologic history and the magnetic susceptibility of rocks, more particularly igneous and metamorphic, should be considered when establishing new observatories.

(To be continued in the December, 1944, number)

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington 15, D. C., August 10, 1944

PRINCIPAL MAGNETIC STORMS

(See also page 212)

Sitka Magnetic Observatory

April to June, 1944

(*Latitude 57° 03′.0 N., longitude 135° 20′.1 or* $9^h\,01^m.3$ *W. of Gr.*)

April 2-6—Beginning about $06^h\,26^m$ GMT, April 2, a disturbance was severe until about 13^h with *K*-indices of 9, 9, 8 being recorded. With the exception of the period between 07^h and 11^h, April 6, when a *K*-index of 8 was reached, activity was moderate.

April 16—A brief disturbance of moderate intensity occurred between 07^h and 18^h GMT, April 16, when *K*-indices of 7, 7, 6, 6 were recorded. Both the beginning and ending were gradual and at no time did motion become rapid.

Harold W. Pinckney, *Observer-in-Charge*

Cheltenham Magnetic Observatory

April to June, 1944

(*Latitude 38° 44′.0 N., longitude 76° 50′.5 or* $5^h\,07^m.4$ *W. of Gr.*)

April 1-3—A disturbance, which at first seemed insignificant, began near 18^h GMT, April 1. At about 06^h, April 2, the disturbance became more violent than any recorded here in some time. After 13^h the storm again was of only moderate severity until it ended at about 09^h, April 3. Two *K*-indices of 7 were recorded during the most violent part of the storm; also an index of 6 for the first three-hour period of April 3.

May 29-30—An unimportant disturbance began indefinitely near the beginning of May 29 and ended at about 08^h GMT, May 30. The outstanding feature was a *K*-index of 6, for the last three-hour period of May 29.

John Hershberger, *Observer-in-Charge*

Tucson Magnetic Observatory

April to June, 1944

(*Latitude 32° 14′.8 N., longitude 110° 50′.1 or* $7^h\,23^m.3$ *W. of Gr.*)

April 1-3—A severe storm began suddenly at $23^h\,25^m$ GMT, April 1, with an increase in H of 22 gammas in about four minutes. Large-amplitude swings in D and H, accompanied by some activity in Z, occurred during the 8-hour period beginning at 05^h, April 2. This was followed by rapid small-amplitude variations for about sixteen hours, the storm ending about 08^h, April 3. Ranges: D, 28′; H, 165 gammas; Z, 50 gammas.

April 15-16—A moderately stormy period of twenty-eight hours' duration began about 14^h GMT, April 15, with the principal activity occurring in the 16-hour interval beginning at 22^h, April 15. Ranges: D, 12′-1/4; H, 104 gammas.

June 20-22—A moderate storm began about 23^h GMT, June 20. During the first six hours there were some fairly rapid fluctuations in H, but the range was not great. The activity ended about 10^h, June 22. Ranges: D, 11′; H, 110 gammas.

J. H. Nelson, *Observer-in-Charge*

LETTERS TO EDITOR

(See also page 158)

ON CONTRIBUTIONS TO THE EARLY HISTORY OF GEOMAGNETISM

Here are a couple of related observations that may be of interest to the JOURNAL in case they have thus far escaped attention:

It appears that one of the earliest of the electrical experimenters, one Otto von Guericke, of the mid 1600's, was led to make his experiments in generating electricity by means of a rotating sulphur globe by having entertained an electrical theory in lieu of the then magnetic conception of the gravity of the Earth. This is brought out in what to me was a charming article upon the subject of von Guericke, by Thomas Coulson, which appeared in the September and October issues of 1943 of the *Journal of the Franklin Institute*. I myself am an appreciative owner of von Guericke's book. . . . I have been hoping that some scholar might eventually find enough interest in the Experimenta Nova to render it into English. . . . Not only would it be interesting to know what von Guericke's ideas really were in this respect, but it is conceivable that since they were not subject to the limiting influence of our subsequent findings and mode of thought, there might be in them some refreshing novelty and suggestiveness.

You probably know of the so-called piezo-electrical phenomenon, the ability of certain crystals to convert mechanical displacement into an electric charge and vice versa by virtue of some little known intimate relation between the structure of the crystal and the electrons thereof. I have recently been looking up in the scientific literature some of the early manifestations of this effect and find they go back to the 1700's. And curiously enough in the earliest of the records I have found the crystal, in this case what appears to be tourmalin, is described as "a magnetical stone." This is because the stone attracted small bits of things when heated. It appears that the application of heat or cold distorts the crystal mechanically and it is this mechanical displacement within the crystal-structure that generates the charge. The earliest appearance to which I refer is in the memoirs of the Royal Academy of Sciences at Paris. The paper in question appears to have been given in the year 1717. It is reprinted below:

"*Of a magnetical stone brought from the island of Ceylan*—There is a little stone, which is found in a river of the Isle of *Ceylan*, about the size of a *French denier*, flat, round, about a line in thickness; brown, smooth and shining, without either smell or taste, which attracts and repells little light bodies, as ashes, filings of iron, and bits of paper; M. *Lemery* shewed it; it is not common, and that which he had cost fifteen livres.

"When an iron needle has been touched with a loadstone, the loadstone attracts the north pole of it by its own south pole; and by the same

south pole it repells the south pole of the needle, thus it attracts or repells different parts of the same body according as they are presented to it, and it always attracts and repells the same.

"But the stone of Ceylan attracts and repells the same little bodies presented to it in the same manner, and it is in this that it differs very much from the loadstone. It seems to have a *vortex* which is not continual, but forms itself, ceases, and begins again incessantly; at the instant when it is formed, the little bodies are driven towards the stone; it ceases, and they continue where they were; it begins again, that is, there comes out of the stone a new *effluvium* of matter analogous to the magnetic, and this *effluvium* drives the little bodies away. It is true that according to this idea the two contrary motions of the little bodies ought to succeed each other continually, which is not the case; for that which has been driven away, is not attracted again. But that which they would have attracted they lay pretty near the stone, and when it repells this body, it drives it to a greater distance. So that what it has once driven away it cannot any more draw to itself, or which is the same thing, its *vortex* has more force to drive away when it is forming itself, than to attract when it is formed."[1]

The point of this item is that here is a case in the early literature of something that later was proved to have been an electrical effect, which has originally been described as a magnetic one, by virtue of attraction. Might there not have been other cases of confusion in the early days between electric attraction and magnetic attraction, and should not one be on the lookout for this in the study of the early literature? Von Guericke's conception of an electrically charged Earth that possessed attraction, appears to have been not an actual confusion in his mind with the magnetic effects but rather an attempt at substitution; nevertheless one can see here in this early thinking a rather close relationship between the two.

It seems clear that in trying to follow some of these early accounts one must not confine himself to what has come to be the accepted meaning of things, which after all contains self-imposed limitations, but rather try to reach out sympathetically and reconstruct the conceptions and yearnings of the day. Thereby it is barely possible that we might get on to some other conceptions, possibly new avenues of approach. For our thoughts of today might well be as dangerous in respect to what they exclude as they are advantageous for what they include.

New York, New York, June 15, 1944 L. Espenschied

[1]The philosophical history and memoirs of the Royal Academy of Sciences at Paris: or An abridgment of all the papers relating to Natural Philosophy, which had been publish'd by the Members of that Illustrious Society, from the year 1699 to 1720. . . . The whole translated and abridged, by John Martyn, F.R.S., and Ephraim Chambers, F.R.S. Vol. 5, pp. 216-217, London (1742).

FIVE INTERNATIONAL QUIET AND DISTURBED DAYS FOR JANUARY TO MARCH, 1944

Reports of geomagnetic activity for the first quarter of 1944 have been received from a sufficient number of magnetic observatories so that the international quiet and disturbed days may be selected in accordance with the method outlined on pages 219-227 in the December 1943 issue of this JOURNAL. The selection is based on the reports of magnetic character on a scale of 0, 1, and 2 from 35 observatories and of K-indices from 23 observatories.

Month, 1944	Quiet					Disturbed				
January	3	4	6	7	30	11	13	14	15	16
February	3	18	24	25	27	7	8	9	14	15
March	1	3	15	17	24	7	10	19	26	27

H. F. JOHNSTON

DEPARTMENT OF TERRESTRIAL MAGNETISM,
CARNEGIE INSTITUTION OF WASHINGTON,
Washington 15, D. C., August 11, 1944

SOLAR AND MAGNETIC DATA, APRIL TO JUNE, 1944, MOUNT WILSON OBSERVATORY

The only magnetic storm recorded at Mount Wilson during April, May, and June began suddenly on April 1 at $23^h\ 25^m$ GCT, and ended on April 3 at about 09^h. The range in H was 180γ. No sunspots were observed from March 31 to April 6.

A slight disturbance began suddenly on April 24 at $01^h\ 15^m$ and ended at about 13^h. The range in H was 60γ. No sunspots were observed from April 18 to 25.

It is to be noted that, in the table of solar and magnetic data, the designation "very bright chromospheric eruptions" is now replaced by "solar flares." This is in accordance with "Solar flares versus bright chromospheric eruptions: A question of terminology," by R. S. Richardson [Pub. Astr. Soc. Pacific, **56**, 156 (1944)].

TABLE I—*Solar and magnetic data*

Day	April 1944						May 1944						June 1944					
	K_2		H_α	H_α	No.	Mag'c	K_2		H_α	H_α	No.	Mag'c	K_2		H_α	H_α	No.	Mag'c
	Whole disk	Central zone	bright	dark	groups	char.	Whole disk	Central zone	bright	dark	groups	char.	Whole disk	Central zone	bright	dark	groups	char.
1	..	..	..	..	0	0	0	0	0	0	0	1	..	..	..	..	..	0
2	..	..	..	..	0	1.5	0	0	0	0	0	0.5	..	..	..	..	..	0
3	..	..	..	..	0	1	0	0	0	0	0	0	0	0	0	1	0	0
4	..	..	..	..	0	0.5	0	0	0	1	0	0.5	0	0	0	1	0	0.5
5	..	..	..	..	0	0.5	0	0	0	1	0	0.5	0	0	0	1	0	0
6	..	..	..	..	0	1	0	0	0	1	0	0.5	1	0	1	1	0	0
7	0	0	0	0	1	0.5	0	0	0	1	0	0.5	1	0	1	1	0	0
8	..	..	..	..	..	0	0	0	0	1	0	0.5	1	0	1	1	1	0
9	0	0	0	1	0	0	0	0	0	1	0	0	..	..	..	..	..	0
10	0	0	0	1	0	1	0	0	0	1	0	0	1	1	1	1	1	0
11	1	0	1	1	0	0.5	0	0	0	1	0	0	1	1	1	1	1	0
12	..	..	..	..	0	0.5	0	0	0	1	0	0	1	1	1	1	0	0
13	1	0	1	1	0	0	0	0	0	1	0	0	1	0	1	1	0	0
14	1	1	1	1	0	0	0	0	0	1	0	0	..	..	..	..	2	0.5
15	1	1	1	1	0	0.5	..	..	..	..	..	0	..	..	..	..	..	0.5
16	1	1	1	1	1	1	0	0	0	1	0	0	..	..	..	..	..	0
17	1	1	1	1	1	0	0	0	0	1	0	0	1	0	1	1	1	0
18	1	1	1	1	0	0	..	..	..	..	..	0	1	0	1	1	1	0
19	1	0	1	1	0	0	0	0	0	1	0	0	1	0	1	1	1	0
20	..	..	1	1	0	0	0	0	0	1	0	0	1	1	1	1	1	0.5
21	1	1	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	0.5
22	1	1	0	1	0	0	0	0	0	2	0	0	1	1	1	1	1	0.5
23	..	..	..	..	0	0	..	..	..	..	..	0	1	1	1	1	1	0.5
24	..	..	..	..	0	0.5	0	0	..	..	0	0.5	1	1	1	1	1	0
25	1	1	..	..	0	0	0	0	0	1	0	0	1	0	..	..	1	0
26	..	..	..	..	..	0	0	0	0	1	0	..	1	0	..	..	1	0.5
27	..	..	..	..	..	0.5	0	0	0	1	0	0	1	0	1	1	1	0
28	..	..	..	..	..	0.5	1	1	1	0	1	0	1	0	1	1	1	0
29	0	0	0	1	0	0.5	1	1	1	1	1	0.5	1	0	1	1	0	0.5
30	0	0	0	1	0	0.5	1	1	1	1	2	0	0	0	1	1	0	0.5
31							..	..	..	..	1	0.5						
Mean	0.7	0.5	0.6	0.9	0.1	0.4	0.1	0.1	0.1	0.9	0.2	0.2	0.8	0.3	0.9	1.0	0.7	0.2

NOTE—For an explanation of these tables see this JOURNAL, 35, 47-49 (1930).

The character-figures of solar phenomena are estimated from the spectroheliograms which are made with a 2-inch solar image, usually in the early morning. Solar flares are reported in these notes if observed at any time during the day.

a, b Formation of a new group which later developed to average size or larger; (a) less than 30° from the center of the disk, (b) more than 30° from the center of the disk.

c, d Solar flares: (c) less than 30° from the center of the disk, (d) more than 30° from the center of the disk.

e, f, g, h, i, j, k, l Passage of a large or active group across the central meridian within 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40° of the center of the disk, respectively.

REVIEWS AND ABSTRACTS

A. H. CORWIN: *Geomagnetic influences on a balance.* Reprinted from "Errors of the Kuhlmann balance," Industrial and Engineering Chemistry, **16**, No. 4, 261-262 (1944).

The possibility that variations in the Earth's magnetic field might influence the zero-point of a balance was apparently first appreciated by Manley,[1] whose invar beam was ferromagnetic. An appreciable error due to the use of steel bearings was also found by McBain and Tanner[2] in a more sensitive balance. The use of magnetic material in the moving parts of a precision balance is to be deplored, yet the Kuhlmann balance has steel screws that are used for adjusting the positions of the knives. Since magnetic field-changes in a modern laboratory may be considerably greater than those resulting from the diurnal variations in terrestrial magnetism which affected Manley's instrument, it was deemed necessary to determine the magnitude of the effect of magnetic field variations upon the Kuhlmann balance.

Experiments—A tangent galvanometer was modified by the removal of its base and its indicating needle in such a fashion that it could be used as the source of a small magnetic field of known intensity. The large coil was supported in a horizontal position on top of the case of the Kuhlmann balance and readings were taken without the current flowing and immediately afterwards with the current flowing but without arresting the beam. Duplication of the experiment gave results concordant within the error of reading of the instrument. Imposing in this manner a vertical field of 1.7 CGS units caused a zero-point shift of ten micrograms. Since the vertical component of the magnetic field at the laboratory was 0.552 unit at the time, the deviation from the true rest-point caused by the vertical magnetic component was 3.3 micrograms. J. A. Fleming, director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has very kindly informed the author that during times of great magnetic disturbances variations as large as 0.02 CGS unit are found in Washington. Using this figure, we should calculate a maximum disturbance of four per cent of the total force or 0.1 microgram, due to variations in the vertical component.

The experiment was repeated with the coil of the tangent galvanometer encircling the case of the Kuhlmann balance at the center and in a vertical position, thus creating a horizontal field parallel to the beam. Imposing a field of 2.28 units caused a change of 69 micrograms. Since the horizontal component of the field at the laboratory was 0.207 unit at the time, the permanent deviation from the true rest-point caused by this field was 6.5 micrograms, corresponding to a maximum variation of four per cent of the amount or 0.24 micrograms.

It is thus apparent that the degree and distribution of residual magnetism in this particular beam are such that the errors caused by the Earth's magnetic fluctuations are smaller than one microgram. On the other hand, magnetic fluctuations caused by electrical installations such as motors, generators, rheostats, or resistance-furnaces may be many times those of the Earth. An analyst using a Kuhlmann balance, or any other with magnetic parts, in the vicinity of electrical installations would have to take precautions to ensure protection against this effect. This could probably be most easily achieved by the use of a soft-iron screen of high permeability and low retentivity.

The magnetic error of the Kuhlmann balance is small in a vertical field because the magnetic screws are symmetrically placed with respect to the knife in the horizontal direction. Thus vertical fields bring about only small torques due to differences between the screws with respect to residual magnetism. The relatively large sensitivity to horizontal fields is caused by the fact that in the vertical direction the screws are unsymmetrically placed, exerting a considerably greater torque above the knife than below it. Occasionally, analytical balances have been found with magnetic pointers. These would cause more serious errors due to the large moment which would be exerted by a force at such a distance from the knife-edge.

AUTHOR

[1]Phil. Trans. R. Soc., A, **212**, 227-260 (1913).
[2]Proc. R. Soc., A, **125**, 579-586 (1929).

PRINCIPAL MAGNETIC STORMS

(See also page 206)

Huancayo Magnetic Observatory

April to June, 1944

(Latitude 12° 02′.7 S., longitude 75° 20′.4 or 5^h $01^m.4$ W. of Gr.)

April 2—A moderate magnetic disturbance began with a small but sharp downward movement in *H* at 05^h 37^m GMT, April 2, which was followed by an irregular decrease to a deep bay at 09^h 10^m. This was followed by a sharp peak thirty minutes later and another even deeper bay just before 12^h. After this time there was only mild disturbance during the daily maximum period and small irregular movements for the rest of the day. *D* and *Z* showed the effect of the disturbance largely by greater ranges than normal for the day.

Paul G. Ledig, *Observer-in-Charge*

Apia Observatory

April to June, 1944

(Latitude 13° 4′.48 S., longitude 171° 46′.5 or 11^h $27^m.1$ W. of Gr.)

April 1-2—This storm began at 23^h 31^m GMT, April 1, and continued until 23^h 50^m, April 2. The maximum in *H* occurred at the beginning of the storm after which it decreased with fluctuations to a minimum at 08^h 46^m, April 2. Thereafter *H* increased with fluctuations until the end of the storm. Vertical intensity was disturbed over the whole period with a minimum at 08^h 21^m and a maximum at 14^h 03^m, April 2. Declination was only slightly disturbed during the period of the storm. *Ranges*[3] *H*, 240 gammas; *Z*, 50 gammas.

H. Bruce Sapsford, *Acting Director*

Watheroo Magnetic Observatory

April to June, 1944

(Latitude 30° 19′.1 S., longitude 115° 52′.6 or 7^h $43^m.5$ E. of Gr.)

April 2—A violent disturbance of short duration began at 05^h 00^m GMT, April 2, with a series of peaks and bays in all three elements followed by a rapid decrease of *H* and westerly *D* and by an increase in the numerical value of *Z*. Between 09^h and 10^h the motions of the *H*- and *Z*-spots were too rapid to record continuously and the *Z*-spot exceeded the limits of registration. After 10^h, *H* gradually increased and *Z* decreased so that by 20^h they were approximately at their normal values, although some small rapid fluctuations persisted until 24^h. Ranges: *D*, 27′.4; *H*, 320 gammas; *Z*, 184 gammas.

May 1—A period of moderate disturbance began with a small movement in all three elements at 05^h 20^m GMT, May 1. After a fairly quiet period of five hours a series of sweeping peaks and bays commenced and extended over the ensuing nine hours. The traces were practically normal by 20^h. The outstanding feature of the disturbance was the peak in the *H*-trace at 14^h 40^m which, with its following bay one hour later, covered a range of 115 gammas. Ranges: *D*, 15′.0; *H*, 115 gammas; *Z*, 92 gammas.

W. C. Parkinson, *Observer-in-Charge*

Magnetic Observatory, Hermanus

January to March, 1944

(*Latitude 34° 25′.2 S., longitude 19° 13′.5 or 1^h $16^m.9$ E. of Gr.*)

January 1—There were disturbances from 09^h to 21^h GMT, January 1. There was a *K*-index of 5 for the fifth three-hour period.

January 5—There were bays on all traces for the first three-hour period January 5, with a *K*-index of 4.

January 9—There were micropulsations from $00^h 45^m$ to $01^h 10^m$ GMT, January 9.

January 10-18—Disturbances which began at about 19^h GMT, January 10, continued until 12^h, January 18. The following three-hour periods had a *K*-index of 5: 21^h-24^h, January 10; 15^h-18^h, January 11; 21^h-24^h, January 15.

January 26—Disturbances occurred from $12^h 30^m$ to $23^h 00^m$ GMT, January 26. There was a *K*-index of 5 for the sixth three-hour period.

January 31-February 7—There were micropulsations on all traces for the following periods: $00^h 30^m$ to $00^h 55^m$ GMT, January 31; $21^h 30^m$ to $22^h 15^m$, February 2; $05^h 05^m$ to $05^h 35^m$, February 5; $00^h 15^m$ to $00^h 35^m$, February 7.

February 7-16—A gradual-commencement storm began at about 06^h GMT, February 7, and continued with many oscillations until the end of February 16. The most disturbed period was from 09^h to 24^h, February 7, during which the *K*-indices were 5, 6, 5, 5, and 5, respectively.

February 20-21—A gradual-commencement storm began at about 08^h GMT, February 20, and continued until 01^h, February 21. There were two *K*-indices of 5 for the periods from 12^h-15^h and 21^h-24^h.

February 28-March 2—There were micropulsations for the following periods: $23^h 00^m$ GMT, February 27, to $01^h 15^m$, February 28; $02^h 25^m$ to $03^h 10^m$, February 28; $03^h 20^m$ to $04^h 05^m$, $16^h 40^m$ to $17^h 10^m$, and $23^h 05^m$ to $23^h 15^m$, March 1; $19^h 25^m$ to $20^h 05^m$, March 2. These micropulsations often appear at the beginning of small bays.

March 4—A disturbance which I describe as a "crotchet" was recorded at $02^h 30^m$ GMT, March 4, and was followed by micropulsations about forty-five minutes afterwards. The *K*-index was 5 for 09^h-12^h. After a period of about thirty hours there were fade-outs on radio reception.

March 5-17—A crotchet-disturbance was recorded on the *D*- and *Z*-traces at 05^h 25^m GMT, March 5. The disturbances which followed continued until 17^h, March 17. The disturbances were of small range. Twenty-one *K*-indices of 4 were recorded in this period. The disturbances were also characterized by small rapid oscillations.

March 18-23—Another crotchet-disturbance was recorded at $07^h 00^m$ GMT, March 18, and the disturbances which followed continued until 24^h, March 23. At first the disturbances were very small. The intensity of the storm increased at 18^h, March 18. *K*-indices of 5 were encountered from 18^h, March 18, to 03^h, March 19, and also 21^h-24^h, March 19. During this period radio reception was poor with many fade-outs.

March 25-29—Disturbances which began at about 09^h GMT, March 25, continued until the end of March 29. The *K*-index was 6 for 00^h-03^h, March 27, and 5 for 06^h-09^h and 12^h-15^h, March 26, and 06^h-09^h, March 27.

A. Ogg, *Magnetic-Survey Adviser*

22. *Magnetic surveys in airplanes by the U. S. S. R.*—In recent years attention has been called by various geophysicists to advantages that would result from magnetic surveys carried out by airplanes among which are aids in geophysical prospecting, obtaining indications regarding depths of basic rock, and delineation of magnetic anomalies. In this connection it is of interest to recall one pioneer effort in this direction, namely an experimental survey carried out in June 1936, under the auspices of the Central Geological Research Institute of Leningrad over the Starorusskoi magnetic anomaly on the Novgorod-Valui line, where, according to data of the Office of the General Magnetic Survey of the U. S. S. R., the vertical component of the Earth's magnetic field varies, over an extension of 60 km, between 250 and 1,400 gammas. The survey was made by A. A. Logachev, an engineer of the Institute, using an instrument of his own construction based on a null-method of measurement in conjunction with a rotating-coil detecting element involving compensation of the main Z-field at the element. Three flights were made over the line at altitudes of 300 to 1,000 m. On all three flights the anomaly was measured with sufficient accuracy. Although the Z-values varied at times from those of the General Magnetic Survey by 500 gammas, nevertheless the delineated profiles gave a precise representation regarding the location and character of the anomaly. [From Information Book on Terrestrial Magnetism and Electricity, No. 3, Leningrad-Moscow, 1937.]

23. *Magnetic surveys of the American Republics*—Joel B. Campbell of the United States Coast and Geodetic Survey has just completed a rather extensive program of magnetic observations at various repeat-stations in South America. At present he is engaged in similar work in New England.

N. O. Parker occupied several repeat-stations in Central America during the early spring and at present is engaged in an extensive repeat-program in Alaska. Fred Keller is working with Mr. Parker. The work in Central and South America and in Alaska has been greatly expedited by using air-transportation between stations.

C. E. Westerman and W. E. Wiles are now engaged in the occupation of repeat-stations in the Western and Pacific States of the United States. They are operating as separate parties.

24. *Comparisons at Huancayo Magnetic Observatory and field-work in Peru*—During June 1 to 4, 1944, Joel B. Campbell of the United States Coast and Geodetic Survey, who engaged on a program of repeat-station observations in South America with the cooperation of the countries concerned, compared his instruments with those at the Huancayo Magnetic Observatory. From June 9 to June 23, P. G. Ledig, Observer-in-charge at the Huancayo Magnetic Observatory together with Lieutenant-Colonel Pedro A. Delgado, and Lieutenant-Commander O. L. Rivera of the Peruvian Army and Navy, respectively, accompanied Mr. Campbell on a trip to the Amazon at Iquitos in connection with his observational program. Advantage was taken of the opportunity to obtain magnetic observations at Chiclayo, Yurimaguas, and Pucalpa.

25. *Magnetic publications*—The United States Coast and Geodetic Survey has in the press the magnetic results for the Honolulu Magnetic Observatory, 1935-36, and for the Tucson Magnetic Observatory, 1935-36. There is also in the press a publication, "The magnetism of the Earth." The latter will replace an older and obsolete publication entitled, "The Earth's magnetism."

26. *Remarkable cloud-to-cloud discharge*—The following information is taken from a recent letter from O. H. Gish: "On the evening and night of July 14, 1944, nearly six inches of rain fell at Seward, Nebraska, about 25 miles northwest of Lincoln. During the storm I saw the longest

cloud-to-cloud discharge that, so far as I can recall, I have ever seen. It was distinctly branched at both ends, subtended an angle of about 90° at an elevation of 30° to 40°."

27. *Magnetic attraction, Gulf of Mexico*—We quote the following from the Hydrographic Bulletin, No. 2862, of July 15, 1944: "An observer reports under date of June 24, 1944, that a compass-error of 15°, which apparently was due to local magnetic conditions, was experienced while steaming a distance of 80 miles after leaving Heald Bank Gas Buoy on a course off Freeport, Texas."

28. *Magnetic disturbances and the Magnetic South Pole in Antarctica*—The following are noted from Sailing directions for Antarctica, 1943 [U. S. Hydrographic Office No. 138, pp. 191 and 248]:

"A very weak directive force has been observed in ships' magnetic compasses in the vicinity of Coulman Island (about 72° 00′ south and 171° 00′ east). The proximity of the Magnetic Pole and the geological structure of the locale are believed to be contributing factors to this phenomenon."

Referring to navigation near Wilkes Land "due to the proximity of the Magnetic Pole, vessels are cautioned not to place reliance upon magnetic compasses when in these waters. Due to the weak horizontal directive force in these areas, compasses will become sluggish and unreliable. The geographic position of the South Magnetic Polar Area in 1909, based on observations, was placed by David in 72° 25′ south and 155° 16′ east. Bage, in 1912, estimated the position to be 71° 10′ south and 150° 45′ east. Mawson, when visiting Cape Denison in January, 1931, estimated the position to be 70° 20′ south and 149° 00′ east. Farr, in 1939, calculated the position to be 70° 00′ south and 148° 00′ east. The 1939 calculations indicate a movement in a northwesterly direction at a speed of about four miles per annum."

In this connection the position as estimated by Ross for 1841 was 75° 05′ south and 154° 08′ east. The first British Antarctic Expedition made the location 72° 51′ south and 156° 25′ east for 1903.

29. *Solar activity and magnetic storms in 1943*—Twenty magnetic storms of range $> 1/2°$ in D, or $\geqslant 150$ gammas in H or in V, were recorded at Abinger [in 1943], as compared with nine in 1942. With few exceptions, including the only "great" storm of the year on August 30-31, the nature of the disturbances of 1943 was characteristic of those occurring around solar minimum: (*a*) Beginning of storms indefinite; (*b*) duration above average; (*c*) tendency to form 27-day sequences; (*d*) a diminished correlation as between storm occurrence and individual sunspots and their associated phenomena in the central zone of the disk. Fourteen of the 20 storms began, however, when the longitude of the Sun's central meridian was between 95° and 215°, indicating a broad "magnetically effective *M*-region" of the Sun. [H. W. Newton in Mon. Not. R. Astr. Soc., **104**, p. 109 (1944).]

30. *Post-war Scientific Command*—A 12-man committee of Army, Navy, and scientific experts are at work on the creation of a scientific high command ranking with the command staffs of the Army and Navy. One of the main objectives is to set up the organization in such a way that it will be responsive to new ideas in warfare and will not be open to the charge of "brass-hat" conservatism and interference. On the Committee which is to plot the scientific command in policy and detail, are four scientists, Dr. J. C. Hunsaker, of the National Advisory Committee of Aeronautics; Dr. F. B. Jewett, of Bell Telephone Laboratories; Dr. Karl Compton, Massachusetts Institute of Technology; and Dr. M. A. Tuve, Carnegie Institution of Washington.

It is the function of this group to decide whether the post-war scientific organization should have its own research projects on contract to

scientific institutions, to determine exactly what relationship it should maintain with the Army and Navy, and to decide how it should be financed.

The form of organization which has received most favorable discussion is that the office should have a Director who would serve a single term of four or five years and a working staff of scientific personnel lent to schools and research institutions.

One of the moving spirits behind the undertaking is Dr. Vannevar Bush, Director of the Office of Scientific Research and Development which has worked in secrecy to produce new and in many cases still secret weapons of the present war.

31. *Committee for the study of Parícutin*—On the recommendation of the Section of Volcanology of the American Geophysical Union, and the indorsement of the Executive Committee of the Division of Geology and Geography of the National Research Council, a new committee of the Division with the title of "U. S. Committee for the Study of Parícutin" has been established.

The purpose of the Committee is to coordinate with Mexican scientists the research on the Parícutin Volcano and to both encourage and facilitate studies in various scientific fields related to the problem. It intends thereby to avoid useless repetition and especially to save from neglect important aspects which depend on the collection of accurate data before activity subsides and the record of eruption is obscured by time. The scope of the proposed investigation includes geological, geophysical, chemical, meteorological, and other scientific studies. The Committee would endeavor to stimulate the interest and the support of scientific organizations and governmental agencies in these various projects.

The membership of the Committee is as follows: Richard E. Fuller, (Chairman); Fred M. Bullard; W. F. Foshag; L. C. Graton; D. F. Hewett; A. G. McNish; Paul A. Smith; O. W. Swainson; C. Warren Thornthwaite; Howell Williams; E. G. Zies; and W. W. Rubey (*ex officio*).

32. *Personalia*—Dr. *Charles G. Abbot*, has announced his retirement, effective July 1, 1944, as Secretary of the Smithsonian Institution after serving for 16 years. Dr. *Alexander Wetmore*, Assistant Secretary, succeeds him as Acting Secretary. Dr. Abbot is widely known for his researches on solar radiation and the application of solar heat to practical purposes.

We learn from *Science* that Dr. *Maurice Ewing*, now engaged in research for the Navy with the civilian rank of "Chief Scientist," has been appointed Associate Professor of Geophysics in the Department of Geology of Columbia University. He will direct graduate instruction in geophysics as a part of a post-war program of geological training and research. He also plans to continue his investigations of the continental shelf and the ocean basins.

At the annual general meeting of the British Physical Society held May 24, 1944, Sir *Edward Appleton* was elected Vice-President, and Professor *S. Chapman* one of the new members of the Council.

The Department of Physics of the University of California at Los Angeles announces that Professor *S. J. Barnett* has retired with the title Emeritus. He will continue his work on gyromagnetism at the California Institute of Technology.

We regret to record the death on June 18, 1944, of Dr. *Harry Fielding Reid*, Emeritus Professor of Dynamic Geology and Geography since 1930 at the Johns Hopkins University, Baltimore, Maryland, at the age of 85 years. He was an associate editor of this Journal from 1902 to 1938, and in 1914 contributed an important paper on "The free and forced vibrations of a suspended magnet" to its pages.

LIST OF RECENT PUBLICATIONS

By H. D. Harradon

A—Terrestrial and Cosmical Magnetism

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Arkhangelsky, A. D. Geological results of the general magnetometric surveys of the U. S. S. R. [Russian text.] Internat. Geol. Cong., Rep. 17th Session, Moscow-Leningrad, 1937, **1**, 241-250 (1939). Abstract, Geophys. Abstr., No. 116, p. 2 (1944).

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